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Backache in Helicopter Aircrew, The Current Situation: A Literature Review

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ABSTRACT

The literature pertaining to the problem of backache among helicopter aircrew is reviewed. Vibration of the helicopter and the posture of the operator are considered as possible causes of the discomfort. Of these causes, the posture and tasks of the pilot are considered to be more significant than vibration. Potential solutions are identified and discussed.

1. *THE PROBLEM OF BACKACHE IN HELICOPTER AIRCREW*

In September 1982, as a result of a request from National Defence Headquarters, Directorate of Preventive Medicine (DPM/NDHQ), the Defence and Civil Institute of Environmental Medicine (DCIEM) undertook to study the feasibility of research into the problem of backache among Canadian Forces (CF) helicopter aircrew. As part of this investigation, DCIEM initiated a survey of the literature to identify approaches to the problem taken by other military authorities.

This report is a summary of the survey of that literature. It has been expanded to include the general literature on two topics which are closely related to the problems of helicopter aircrew. These are the medical problems of the human spine, and the human response to vibration.

1.1. *The Tasks of the Helicopter Pilot*

The following description of the operation of a helicopter is drawn from Skjenna,[1] Delahaye and Auffret,[2] and the document "Aircraft Operating Instructions - Kiowa CH 136", the last of which is issued by the Department of National Defence, Canada.

The special ability of the helicopter to hover in a fixed place, and the ease with which it can be moved in any direction relative to its axis while in flight have found applications in many military and civilian operations. These include hovering close to the ground for military reconnaissance or attack missions, landing on a precise spot among trees or other nearby obstructions to effect a rescue, or the close inspection of high-tension electrical lines.[1] The pilot may have to fly for extended periods of time so close to the ground or forest that his attention is constantly required to avoid contact with hazards such as over-head wires. These specialized missions take up a large part of a helicopter pilot's flying time, and preparation for them is an important aspect of helicopter aircrew training.

The pilot's task in this stressful environment is made more difficult by the flight characteristics of the helicopter.

> "Flying qualities that would be considered totally unsatisfactory by fixed-wing standards are normal for helicopters. Helicopter pilots are living evidence that an unstable aircraft can be controlled. Also, they are evidence that control without stability requires constant attention and results in considerable pilot fatigue."[3]

In view of the constant hazards and demands, helicopter flying is generally considered to be more difficult than flying a fixed-wing aircraft. Helicopter aircrew duty is regarded as specially taxing and, not surprisingly, helicopter accidents occur more frequently than those involving fixed-wing aircraft.

1.1.1. *Helicopter Controls*

Flight control of a helicopter is accomplished with three controls; two manually-operated levers and a pair of pedals. Vertical lift is controlled by adjusting the pitch of the blades simultaneously by using the ***collective*** pitch lever which normally is mounted on the left side of the pilot seat, with the lever hinged at the rear. The direction of the rotor thrust is controlled by cyclically altering the pitch of each blade in step with its rotation about the hub of the rotor, resulting in an effective tilt of the main rotor system. The direction and degree of tilt is controlled by the ***cyclic*** stick, which is usually mounted near the floor of the helicopter directly in front of the pilot, the cyclic handle rising between the pilot's knees. The control arrangement is such that the rotor tilts in the same direction that the cyclic stick is deflected.

The foot pedals are used to control the rotation of the helicopter in the yaw plane and counter-act the torque of the main rotor by varying the thrust of the tail rotor (in helicopters with one, rather than two, main rotors).

Rotor speed is critical and must be controlled within specific limits at all times in flight in order to maintain control of the helicopter. In most helicopters, the engine throttle is a hand-operated twist grip attached to the collective lever. In helicopters with piston engines, continuous manual adjustment of the throttle is required to compensate for changes in rotor pitch to keep the rotor speed constant. In turbine-driven helicopters, such as the CH-136 Kiowa, the throttle is automatic; a nearly constant engine speed is maintained by a system which adjusts the engine power to match the load.

In actual operations, the pilot must maintain continuous control over both levers and the pedals. For example, to increase his forward speed, he must move the cyclic forward, raise the collective, and adjust the pedals to compensate for the increased torque on the helicopter from the main rotor. In a piston-driven helicopter, the pilot must also adjust the throttle to compensate for the increased engine load. No other vehicle requires the continuous adjustment of all of the operator's four limbs for normal control.

Another aspect of the helicopter controls is the fineness of control required in many flight phases, particularly in hovering. In hovering, the helicopter tends to be unstable.[1] Therefore, minor adjustments of the controls lead to changes in the position and attitude of the helicopter which must be continuously monitored and compensated. Pilots are instructed to place the right elbow on the right knee to steady the right hand when operating the cyclic. Some pilots operate the collective lever by hooking the fingers of the left hand around the lever and bracing the thumb against the seat frame. The purpose of these strategies is to isolate the controlling hands from gross movements of the body which may be induced by sudden movements of the aircraft, or simply by efforts to see around the aircraft.

1.1.2. *Helicopter Operator Posture*

The position of the control levers in the cockpit, together with the requirement that they must be continuously operated, imposes a posture on the pilot which he is unable to change without affecting the operation of the helicopter.

Those aspects of the posture which are judged to contribute most to the pilot's discomfort are the hunched position which must be assumed in order to rest the elbow on the knee, and the bending to the left which is required in order to reach the collective lever when it is near its lowest position. The "helicopter hunch" is dictated by the fact that, with a normally-extended spine in the seated posture, it is impossible for most people to rest the elbow on the thigh.

The degree to which the pilot must bend in order to reach the levers depends on his own body height and anthropometry, the seat height and the position of the levers. Delahaye *et al.*[2] describe the different postures required in different helicopters used by the French armed services. It is apparent that some helicopters are better than others in this respect and also that there are no rigid standards in effect worldwide for control positions.

In order to see directly forward, the pilot must extend his neck backward in order to compensate for the forward angle of his torso imposed by the controls. This may contribute to the neck pain noted by Delahaye *et al.*[2]

It should be noted that, with all of his limbs involved in operating the helicopter, it is extremely difficult for a pilot to alter his seating position. It is normal for seated humans to adjust their seating position frequently, in order to redistribute the load on the buttocks and the postural muscles, to prevent fatigue. A position which initially may be fairly comfortable, becomes painful if there is no opportunity to relieve constantly tense muscles or areas of the buttocks which continually bear the weight of the torso.

1.2. *Incidence of Backache among Helicopter Aircrew*

The most comprehensive recent report on the extent of back problems among helicopter aircrew is by Delahaye *et al.*[2] who cite the results of surveys in France, the United Kingdom, Belgium, the Federal Republic of Germany and the United States of America. All of the surveys show that a significant fraction of helicopter operators suffer from back pain. Goede[4] has described the backache among helicopter aircrew in the Canadian Forces, and there are articles from United Kingdom,[5,6] West Germany,[7] Italy,[8] and the Union of Soviet Socialist Republics[9] on the same problem.

The incidence of back pain, that is, the fraction of aircrew reporting pain varies greatly from survey to survey. The lowest incidence, 21%, was reported by Rance and Chappelow[5] in 34 subjects in the United Kingdom, and the highest, 95%, is from a West German study[2] Some authors[2,5] have reported variations in incidence with the type of helicopter, the type and duration of missions,[2] and the experience of the aircrew. A recent report by Froom *et al.*[10] showed that low back pain and spondylolisthesis† were significantly more prevalent among a group of Israeli helicopter pilots than in a similar group of cadets.

There are other occupational groups in which an increase in the likelihood of backache is proven or suspected. These groups include tractor drivers,[11] heavy equipment operators,[12] bus drivers,[13] and truck drivers.[14,15] Among military personnel, drivers of Armoured Personnel Carriers in the Canadian Forces have a higher-than-normal incidence of backache and related disorders.[16] Some of these groups, such as tractor drivers and heavy equipment operators, are exposed to vibration and postural constraints similar to those of helicopter pilots.

The studies of these large groups of workers have been designed to determine whether the incidence of backache and related disorders is greater in the affected group than in the general population, rather than to find out the fraction of the affected population who actually suffer from backache. Sandover[11] cites a report by Rosegger and Rosegger[17] who found that 75% of a sample of tractor drivers reported that they suffered from backache. Apart from this datum, it is difficult to compare the extent of the backache problem among helicopter aircrew to that of the similar problems of ground vehicle operators.

1.3. *Symptoms of Backache Induced by Helicopter Operations*

According to Delahaye *et al.*,[2] the most common form of the complaint is a chronic ache in the lumbar area. The discomfort is characteristic of spinal disorders in that it is aggravated by lifting or being seated in vehicles, and relieved by lying down and by physiotherapy.

Patients with more advanced effects experience severe pain during helicopter flight which makes flying very difficult. In the final stages the pain becomes permanent and is accompanied by spasm of the paravertebral muscles in the area of the lumbar spine.

In about half of the patients, episodes of acute pain and spasm occur along with the chronic pain.[2] These episodes may be brought about by events unrelated to helicopter operations, such as lifting and tend to recur. About 2% of the patients experience sciatica or other signs of intervertebral disc dislocation or injury.

Delahaye *et al.*[2] also mention occurrences of pains in the thoracic area and the neck. These may be caused by the use of survival packs strapped on the back and by the additional weight of a protective helmet.

Radiologic examination of helicopter pilots experiencing backache[2] showed that a mild scoliosis (lateral curvature of the spine) without rotation of the vertebral bodies was common. Since scoliosis is common in the general population, it is unlikely that this is, by itself, evidence of a pathological change.

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† See the Glossary in Appendix A for definitions of the anatomical terms used in this Section.

Similarly, the signs of osteoarthritis found in some of the patients did not appear to be directly related to their pain or a special consequence of their having flown in helicopters.

1.4. *The Development of Backache in Helicopter Aircrew*

According to Delahaye *et al.*,[2] there is considerable variability in the time required for the first symptoms of backache to appear. There are several factors which influence whether or not pain is felt:

a. total flying time,

b. total flying time in a month, in a day or in a single continuous flight,

c. the type of helicopter and the type of flying mission (e. g. hovering vs. forward flight),

d. and the individual pilot.

Delahaye *et al.*[2] state that there are threshold values for the total hours of flight in a given period, below which backache does not occur. These thresholds depend upon the individual, but average values are:

a. 30 to 40 hours per month

b. 3 to 4 hours per day

c. 1.5 hours of continuous flight.

The average of the total flying hours experienced by pilots before the appearance of backache is given by Delahaye *et al.*[2] for several studies conducted by French investigators. Earlier studies reported as little as 300 hours flying time before backache appeared, but more recent studies give average values between 1000 and 1500 hours. The difference between these figures may be the result of improved helicopter design. It is important to note that the average values do not necessarily apply to each individual; one pilot with a spinal anomaly experienced pain after only 20 hours of flight.

2. *THE VULNERABILITY OF THE HUMAN SPINE*

The phenomenon of backache in helicopter aircrew must be considered with the problem of backache in the general population in mind. Back pain, particularly in the lumbar region, is one of the most common ailments of man. Recent surveys, reviewed by Andersson,[18] and by Frymoyer and Pope[19] show that:

a. Sixty to eighty percent of the adult population experience back pain at some time in their lives, and it occurs most often in persons whose ages are between thirty and fifty.

b. According to a British survey, back pain accounted for 13 million consultations with doctors in one year in that country and 6000 surgical operations.

c. Back pain was responsible for 3.6% of all sickness absence days in Great Britain in 1969-1970. The number of chronically disabled persons in that country was 79,000 in 1971. In the United States, a different survey has shown that back pain reduced work capacity by an average of 28.6 man-days per year per 100 employees and was the most common cause for limitations in activity in persons under 45 years of age.

It is plain that back pain is a widespread problem, and physicians should not be surprised to see it among helicopter aircrew. *The complete elimination of back pain among aircrew may also be an unrealistic goal.*

However, the prevalence of back pain among the general population has led to a large body of literature on its possible causes, treatment, and prophylaxis, which will be useful in the study of back pain among helicopter aircrew. A detailed comparative study of the incidence of back pain among helicopter aircrew and the general population may show that, among the aircrew, the onset of back pain is earlier and the symptoms are more severe. The pattern may be similar to that found by Milby and Spear[12] and Spear *et al.*[20] for heavy equipment operators.

2.1. *The Anatomy of the Lumbar Spine*

The five lumbar vertebrae are the lowest separate vertebrae of the human spine (Figures 1 and 2). The lowest, L_5, is directly above the sacrum, which articulates with the pelvis. They are the largest vertebrae, together making up one-quarter of the length of the spine.

The detailed anatomy of the vertebrae is complex, and changes from one vertebra to the next. It is described by Finneson[21] and by Delahaye and Auffret.[22] In a simplified form, the spine can be thought of as a vertical load-bearing column in parallel with a hollow tube for the spinal cord.

The load-bearing column consists of the vertebral bodies, which are like a stack of bony cylinders, and the intervertebral discs. Each intervertebral disc is composed of a gel-like mass, called the *nucleus pulposus*†, surrounded by a ring of fibrocartilaginous material, called the *annulus fibrosus*. The *annulus fibrosus*, together with the cartilaginous plates which cover the upper and lower surfaces of the discs, enclose the *nucleus pulposus* to form a structure like a gel-filled cushion.

The lumbar intervertebral discs are the thickest in the spine and make up one-fifth of the length of the lumbar spine. This is significant in understanding the cushioning properties of the spine, as well as in understanding the mechanisms of low-back injury.

The hollow column which encloses the spinal cord is made up of the vertebral arches. Each vertebral arch bears articular processes, which form the joints between the vertebrae at the rear, and the lateral and spinous processes which serve as anchors for the ligaments and muscles of the spine.

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† See the Glossary in Appendix A for definitions of the anatomical terms used in this Section.

The vertebrae articulate with each other at the articular facets, which are part of the articular processes. The articulations of the lumbar vertebrae are in the sagittal plane, an orientation which would tend to resist rotation in the coronal plane. However, the facets are loosely coupled by the ligaments, and some rotation of the vertebrae relative to each other is possible.

The spine is almost completely enclosed by ligaments which surround the vertebral bodies and link the processes of the vertebral arches. The anterior longitudinal ligament runs vertically along the front surfaces of the vertebral bodies, linking them at the epiphysial rings (the margins of the bodies next to the discs).[21] It is considerably larger and stronger than the posterior longitudinal ligament which joins the vertebral bodies on the dorsal side, within the vertebral canal. There are also lateral vertebral ligaments which link the intervertebral disks at the sides.

An important aspect of the geometry of the lumbar spine is its anatomical relationship to the spinal cord. The foramina of the lumbar vertebrae, through which the spinal cord passes, are not all circular. Finneson[21] shows that the nerve roots arising opposite the fourth and fifth lumbar vertebrae lie in bony recesses on the sides of the foramina. In this position, they are especially prone to compression from a herniated disc.

The lumbar spine is supported and surrounded by a large number of muscles. Some of the muscles, such as the *multifidus* are complex muscle groups, which have elements arising from every vertebra. The complexity of these muscles, and the interrelationship of their functions, make it difficult to understand the contribution of each muscle to the support and motion of the spine. Muscle groups which are posterior to the column of the vertebral bodies generally act to extend the spine; i. e., to cause it to curve backwards. These include the *Quadratus Lumborum*, the *Sacrospinalis*, the *Multifidus*, the *Intertransversearii* and the *Interspinalis* muscles. The spine is flexed by the action of the muscles of the abdominal surface; there being no muscles directly attached to the vertebrae in a manner which would flex the spine. In addition to flexing the spine, the muscles of the abdominal surface, the internal and external oblique muscles, the *transversalis*, and the *rectus abdominis*, form a "natural girdle" around the internal organs of the abdomen, and can modify the internal pressure of the abdominal organs.

Some of the extensor muscles of the spine are paired on either side of the body. The spine can be curved to one side (abducted) by action of the extensors on that side. The *psoas* muscles lie on either side of the lumbar spine. The *psoas major* muscle extends between implants on the sides of the lumbar vertebrae and the lesser trochanter of the femur. It can also act to abduct the lumbar spine.

The human spine has a natural curvature. The curvature of the lumbar spine in a standing person is concave to the rear, or lordotic. The lumbar lordosis disappears when a person sits down in normal circumstances. The curvature may have developed to improve the shock-absorbing capability of the spine, or it may be the result of man as an animal only recently (in evolutionary time) assuming an upright posture.

2.2. *The Mechanics of the Spine*

The human lumbar spine performs several functions. It is primarily a load-bearing column, supporting the head, arms and thorax. It must also support loads carried by the arms. The body motions involved in reaching and lifting require that it be flexible. An important function of the spine, particularly for helicopter pilots, is that it is a shock absorber. Long before the invention of vibrating transport systems, man used his spine to absorb the shocks of foot-strike in walking, running and jumping. The anatomy of the spine, described above, is adapted to performing these functions, but the spine does not perform them alone. It requires assistance from the muscles of the trunk and abdomen to perform the most basic lifting tasks. The spine is very vulnerable to failure from excessive loads or inadequate assistance from the muscles.

The main load-bearing elements of the spine are the vertebral bodies and the intervertebral discs, although the articular facets contribute somewhat to the load-bearing ability of the spine.[23, 24]

The mechanical properties of these elements have been extensively studied[25] in isolated vertebral units as well as complete excised spines.

The response of the intervertebral disc to pure compression shows two unique features. First, it increases in stiffness with increasing force,[25] and secondly, the stiffness increases with increasing speed of loading. This characteristic is believed to be responsible for the fact that under rapid loading, such as during ejection seat operation, the vertebral bodies are fractured without signs of damage to the discs.

The fluid-filled centre of the disc transforms compressive forces acting along the length of the spine into outward pressure on the *annulus fibrosus*, which causes it to bulge outward. The nucleus itself is nearly incompressible, so this mechanism is responsible for much of the elastic behaviour of the disc. Over time, the nucleus can gain or lose fluid depending upon its internal pressure. This results in the average person being somewhat shorter at the end of the day than in the morning after bed rest. This change in length with load has been investigated in excised spinal segments by Kazarian.[26]

The ligaments of the spine act to stabilize the spine but are not sufficient by themselves to enable it to carry the normal loads of the trunk. The muscles of the spine are necessary to maintain normal stability in the upright posture.

The load on the spine can be estimated by measuring the pressure in the liquid *nucleus pulposus* of the intervertebral disc. This measurement has been performed in a large number of subjects by Nachemson and his colleagues.[27, 28] These measurements show that the compressive load on the spine is about 1.5 times the expected forces on it in a standing person. This is probably the result of the tension of the ligaments and muscles required to stabilize the spine.

The compressive load on the lumbar intervertebral discs increases when a standing man sits down, and further when he slouches forward. The maximum compressive load in the slouched position is about 180 % of the load in the standing position. This may be the result of an increase in the tension of the articular ligaments when the lumbar spinal curvature changes from the lordosis of standing to the kyphosis of sitting.

When a person leans forward to lift an object, the spine is assisted in bearing the load by the abdominal muscles.[25] The abdomen is compressed by the action of these muscles and the diaphragm to form an relatively rigid object between the pelvis and the thoracic cage, which serves as an alternative load-bearing path from the arms to the legs. This reduces the tension in the extensor muscles of the spine required to stabilize it against flexion. Weakness in the abdominal muscles can greatly increase the tensions required in the spinal extensors and can contribute to injurious forces on the spine itself.

2.3. *Disorders of the Lumbar Spine*

It is impossible to review here all of the congenital or acquired malformations or diseases of the lumbar spine. A few, however, are believed to contribute to low-back pain and are relatively common. These are lumbar disc degeneration, lumbar disc herniation, and, possibly, a number of malformations of the lumbo-sacral region.

It appears to be normal that the lumbar intervertebral discs degenerate with age. This degeneration involves a loss of fluid in the *nucleus pulposus* and a loss of strength in the *annulus fibrosus*. This degeneration will cause a loss of height in the disc and may eventually lead to its collapse or make it more vulnerable to herniation.

Herniation of the lumbar intervertebral discs may be the result of degeneration accompanied by severe loading. The disc usually bulges or ruptures into the spinal canal through its posterior surface. The bulge may entrap the nerve roots of the motor and sensory nerves of the lower body and legs, causing intense pain in the area served by the nerves, or paralysis or paresthesias (tingling or "pins & needles" sensations). Sciatica is a well-known form of this phenomenon.

The clinical conditions which can cause low-back pain are too numerous to mention here.[29] The most common form of low-back pain is called "idiopathic low-back pain" because it is not

related to specific causes such as malformations or cancer. The symptoms, as described in textbooks, are the same as those given for helicopter pilots' backache in Section 1.3 above. This form of low-back pain has been the subject of many studies, but the cause is not known for certain in all cases. Nachemson[30] makes a strong case for the failure of the lumbar intervertebral disc, either through degeneration or rupture, as the cause of most low-back pain. The disc itself is not innervated, but the ligaments surrounding the disc have pain-sensitive nerves. An alternative mechanism for pain may be the stresses on the articulations of the vertebral arches caused by the geometric changes in the vertebrae. The pain may lead to muscular contractions, which themselves may lead to spasm and further pain. Nachemson notes that the first signs of disc rupture occur in persons at ages near 25 years and it is at this age that low-back pain first appears. Those situations which would tend to increase the load on the lumbar intervertebral discs also increase the likelihood of low-back pain. These include pregnancy, obesity, work involving lifting, and work involving long periods of sitting. Patients with ruptured lumbar discs often have a history of low-back pain.

Certain disorders of the spine lead to a greater likelihood of low-back pain. Spondylolysis is a fracture of the vertebral arch of the lowest lumbar vertebra. The body of this vertebra is tilted forward at an angle of about 30 degrees to the horizontal, and the failure of the arch can allow the body to move forward relative to the sacrum below it. This condition is called spondylolisthesis. Spondylolysis and a small amount of spondylolisthesis may occur in healthy persons without causing symptoms. However, it is more common among sufferers of low-back pain than in the normal population.

Delahaye and Auffret[31] describe the procedure used in the French forces for screening candidates for pilot training for spinal abnormalities which may be conducive to low-back pain. More is given on this subject in Sub-Section 4.2.1.1.

3. *VIBRATION AS A CAUSE OF BACKACHE IN HELICOPTER AIRCREW*

3.1. *The Effects of Vibration on Man*

Vibration is usually defined as the oscillation of a solid object at frequencies between 1 and 80 Hz. There are two general ways in which man is exposed to vibration; vibration of the structure which supports him and vibration of an object held in his hand or otherwise touching him. The former kind, sometimes called "whole-body" vibration is most relevant to the problems of helicopter pilots and has been most thoroughly investigated. Vibrations at frequencies above 80 Hz, if they are at all tolerable, will be perceived as noise; whole body oscillations at frequencies less than 1 Hz are more likely to induce motion sickness rather than the peculiar biodynamic effects of vibration.

Within this range of frequencies are vibrations to which man is exposed frequently while travelling or operating machinery. This exposure may have many different effects. The human body responds dynamically to the vibration of the structure supporting it in ways that are similar to the response of a mechanical system of masses linked by elastic springs and energy-absorbing elements. Such a system may respond with an exaggerated motion, because of resonance with the vibration of the support, or it may respond with motions less intense than that of the support, because of the attenuation of the vibration by elastic and energy-absorbing components. Similarly, parts of the human body may resonate at the frequency of the applied vibration and respond with motions which are larger in amplitude than those of the support.

Secondary to the dynamic response, there will be physiological effects. The function of muscles, nerves, respiration and even of the bones and ligaments will be affected. The immediate effects will be changes in perception and behaviour, and possibly fatigue and pain. The long-term effects may be disease of the bones and their supporting structure brought about by the repeated forces induced by the vibration.

3.1.1. *The Biodynamic Effects of Vibration*

The general effects of whole-body vibration on man have been reviewed by several authors[32-37] and it is difficult to condense all the observations on the subject. There are two general measures of the physical response of man to vibration. *Impedance* is the ratio of the applied force on the body to the velocity of the resulting motion. *Transmissibility* is the ratio of the motion at some part of the body distant from the vibrating support to the motion of the support.[34] The human body responds to vibration in a manner which is strongly dependent upon the frequency of vibration and somewhat dependent upon the position of the body. Measurements of transmissibility[38] show that the body has one or more strong resonances in the range of frequencies between 4 and 8 Hz. It is not possible to be more specific, as the actual frequencies are strongly dependent upon individual factors such as weight, muscle tone and posture.

There are two systems which contribute to this resonance. One is the motion of the abdominal contents within the elastic limits of the diaphragm and the abdominal wall.[38] This resonance is most evident during horizontal oscillations of subjects lying on their backs. The other resonant system consists of a vertical motion of the rib cage and shoulders relative to the hips. This resonance can lead to motions of the shoulders which have an amplitude up to four times the amplitude of motion of the pelvis.[34] This resonance may be one source for the discomfort of helicopter pilots, since the elastic elements of the spine are most heavily stressed by this motion.

At higher frequencies of oscillation, between 12 and 20 Hz, the head moves in a resonant fashion in response to vertical vibration. These frequencies are most likely to cause deterioration of vision.

In response to horizontal vibration in either axis, the entire upper body tends to sway. The effect is greatest at frequencies below 6 Hz.[39]

There have been numerous efforts to model the human response to vibration. These have been reviewed by Allen,[40] Griffin,[41] and Lange.[42] Most vibration response models exist for the purpose of predicting the effects of vibration on performance (e. g., manual control) or passenger comfort. There has been very little effort to use models to predict possible traumatic effects of vibration.

3.1.2. *The Physiological Effects of Vibration*

Vibration has a direct effect on respiration which is due to the displacement of the abdominal organs.[43] In addition, there appears to be a tendency for seated subjects to hyperventilate when exposed to vibration, which manifests itself as changes in minute ventilation,[44-46] and, with long exposures, produces a definite hypocapnia†.[47] Guignard[47] explains the hyperventilation as the consequence of overstimulation of mechanical receptors in the body, rather than the direct consequence of vibration-driven airflow in the lungs. It may have an effect upon the performance of persons exposed to vibration, particularly pilots at high altitudes, but this has not been systematically studied.

With more severe vibration, there is a definite increase in oxygen uptake.[45, 48, 49] The increase in oxygen uptake is a result of a generalized increase in muscle tone and activity during vibration exposure.[49] This increase is only partly related to the effort to maintain posture. This is a possible mechanism for the generation of fatigue and muscle pain among humans exposed to vibration.

3.1.3. *The Effect of Posture on Human Vibration Response*

The obvious hypothesis that posture affects the response of man to vibration has only recently been investigated in a systematic way. Griffin[50] measured seat-to-head transmissibility on a small number of seated subjects exposed to vertical vibration, and found that they could change transmissibility by a factor of six or more through changes in posture. He found that subjects tended to adjust their position and muscle tone in order to shift their natural resonance frequencies away from the driving frequency.

Rowlands[51] exposed subjects to vertical vibration in a seat with a rigid back. At frequencies near 4 Hz, the subjects could reduce transmission to their heads by sitting erect so that the shoulder resonance was damped by the pressure from the seat back. At higher frequencies, near 20 Hz, the subjects reduced their transmissibilities by slouching so that they were not in contact with the seat back. Oborne and Boarer[52] found no significant difference in the subjective response to vibration related to the difference between an erect and a slouched posture in a seat without a back. Similarly, Griffin[50] found that individual subjects on a seat without a back found very different postures to be ideal from the point of view of subjective comfort. The effect of seated posture on vibration response should be explored more fully in a variety of seating conditions.

3.1.4. *The Effect of Vibration on Subjective Comfort*

"Comfort" is a subjective phenomenon which can be described in several ways and is affected by many causes. Guignard[53] points out that subjective comfort may be greatly altered by whether or not the person exposed expects the vibration as normal to his or her environment. The sources of discomfort induced by whole-body vibration depend upon the frequency and direction of the vibration. At low frequencies near the 4 - 8 Hz body resonance, human tolerance to vertical vibration is limited by difficulty in respiration and chest pains induced by the motion of the abdominal contents.[37] At frequencies between 12 and 20 Hz, the resonance of the head may

† See Glossary

cause headaches, vision disturbances and dizziness. At still higher frequencies, tingling sensations in various body parts directly in contact with the source of vibration may be objectionable. At any frequency, abrasion against supports or restraints can injure the skin.[37]

There have been many studies of the relative "subjective comfort" of vibrations of various kinds. The use of "subjective comfort" as a measured or controlled variable in vibration studies serves several purposes:

1. It serves as an index of relative human tolerance; that is, if two vibrations at different frequencies or in different directions produce equal "subjective discomfort" at different amplitudes, then the ultimate human tolerance to the two vibrations is likely to be found at different (and perhaps proportional) amplitudes.
2. It is relatively easy, in a sense, to measure subjective comfort, if one chooses the appropriate test method. Subjects are instructed to compare the relative discomfort of two vibrations, or to adjust the amplitude of a test vibration so that it produces discomfort equivalent to that of a standard vibration. This poses some problems: can a subject quantitatively compare the effects of a 20 Hz vibration on his vision, with that of a 4 Hz vibration on his spine and viscera?
3. Subjective comfort is very relevant to the definition of standards for vibration in passenger vehicles and aircraft.

Guignard[53] has reviewed some early investigations into the effect of vibration on comfort. Magid, Coermann and Ziegenruecker[54] explored the limits of the tolerance of seated subjects (in an aircraft cockpit seat) to vertical vibration at frequencies between 1 and 20 Hz. More recently, Miwa,[55] Jones and Saunders,[56] and Shoenberger and Harris[57] measured contours of "equal sensation" for vertical vibration of seated subjects. The general shape of the curves of ultimate tolerance and equal discomfort reflects the pattern of impedance and transmissibility curves (Figure 3). Human tolerance to vertical vibration is at a minimum, about 1 g root-mean-square (rms), at frequencies between 4 and 8 Hz. The acceleration amplitude of tolerable vibrations increases to about 7 g rms at 14 Hz and higher with increasing frequency.

There have been numerous experiments measuring the relative comfort of subjects exposed to random vibrations,[58-60] and vibrations in various directions, including certain types of angular vibrations.[61-68] Studies have also been performed of the effects of subject posture[52] and seat back angle[69] on subjective comfort.

The results of these studies are difficult to express concisely. Many of them are attempts to expand the scope of the International Organization for Standardization (ISO) Standard 2631 (see Section 3.3 for details) to include environments in which the vibration is composed of multiple frequencies in multiple directions. These vibrations are more often encountered in real life than the unidirectional sinusoidal vibrations used in earlier experiments.

3.1.5. *The Effects of Long-Term Exposure to Vibration on Health*

Apart from the effects on the spine which are described below, long-term exposure to whole-body vibration may cause gastro-intestinal and ano-rectal disorders.[70] Vibration applied locally to the hands causes Raynaud's phenomenon, a clinical problem of the circulation among operators of devices such as chain saws and pneumatic drills. Raynaud's phenomenon is a spasm of the arteries of the fingers which occurs in response to exposure to cold. The affected fingers become pale because of the loss of blood flow.[70] To the knowledge of the author, these effects of vibration have not been noted among helicopter aircrew.

3.2. *The Effects of Whole-Body Vibration on the Lumbar Spine*

Recently, because of the prevalence and costs of low-back pain, there have been a number of investigations into the possible association of low-back pain with certain occupations, such as driving or manual labour. Several occupational groups whose work exposes them to vibration

while they are seated show significantly increased susceptibility to low-back pain and related diseases. Operators of heavy machinery,[12, 15, 20] tractor drivers,[17] and people who spend a large part of their time driving[11, 13, 14, 71] are at increased risk of low-back pain. The difference between the populations of developed and undeveloped countries in the incidence of low-back pain has been attributed to the prevalence, in the developed countries, of the use of vehicles and exposure to whole-body vibration.[72]

There are several hypotheses attempting to explain the prevalence of low-back pain among occupational groups, including helicopter aircrew, who are exposed to whole-body vibration. An important consideration in the study of this problem is that all of the groups studied so far, whose work exposes them to whole-body vibration, are exposed while in a seated position, and while they are controlling a vehicle. The seated position itself, in the absence of vibration, increases the stress on the spine. The pelvis is rotated towards the back in the seated position, and the normal curve of the lumbar spine is altered.[73] The intervertebral discs may be more susceptible to loads in this position. The muscular effort required to control the vehicle, as well as that required to orient the head and upper body for adequate vision, will add to the stress.

Shanahan and Reading[74] have recently found that backache can be produced in helicopter pilots just as easily by having them seated in a non-vibrating simulator and performing a simulated control task, as by having them seated in the same simulator when it is reproducing the vibration of an operational helicopter. This suggests that it is posture, rather than vibration, which is responsible for the backache. In support of this suggestion is the observation by Sandover[11] that the shocks delivered to the pelvis by rapid walking and running often exceed in amplitude vibrations which would be considered well beyond the comfort limits of ISO 2631, yet they do not appear to cause abnormal back pain.

Sandover[11] has reviewed the current hypotheses about the relationship between mechanical stress on the spine and lumbar intervertebral disc degeneration, which is the most likely cause of low-back pain. Mechanical stress may hasten the degenerative changes in the spine through microscopic injuries to the epiphyseal surfaces of the vertebrae, through which the intervertebral discs are nourished.[75] Alternatively, continual exposure to mechanical stress may cause the viscoelastic elements of the lumbar disc to be stretched to the point of mechanical failure. It is not yet possible to determine whether either or both of these mechanisms can lead to lumbar disc failure.

3.3. *The Effects of Vibration on Performance*

3.3.1. *The Effect of Vibration on Vision*

The chief effect of vibration on vision is to cause the image projected upon the retina to oscillate rapidly, thus blurring the perceived image because of the finite speed of response of the retinal photoreceptors and their associated synaptic cells and nerve-fibre tracts. This effect can arise from vibration of the object as well as through whole-body vibration. What matters in whole-body vibration is the transmission of vibration to the head. As mentioned above in Sub-Section 2.1.1, this transmission is greatest at 12-20 Hz, and is strongly affected by posture and the nature of the seat.

Griffin[76] studied the effects of vibration on vision in pilots flying the British Army "Scout" helicopter. After measuring the intensity of the vibration in the helicopter and performing laboratory studies on the pilots, he concluded that the helicopter vibration was not a potential cause of visual blurring. To be specific, at no single frequency above 7 Hz was the vibration of the helicopter greater than the threshold intensity required for visual impairment by blurring. However, at 7 Hz, i. e., at the rotor blade frequency, the level of vibration was just nearly enough to cause perceptible blur.

The problem is complicated by large individual variations in transmissibility and the effects of multiple frequency vibration and angular vibration of the pilot's head. In actual tests, he found no decrement in visual acuity when the subject was riding a hovering helicopter, as

compared to the acuity when the helicopter was on the ground.

Griffin and Lewis[77] have recently reviewed experimental data on this subject. There are many complicating factors to estimations of the effect, including object size, viewing distance, illumination and the means of applying the vibration. Generally, the eyes compensate for low-frequency vibration below about 6 Hz, but the task of compensation may lead to fatigue and blurring. At higher frequencies, the blurring is dependent upon posture and frequency of vibration, but there is little effect of fatigue.

3.3.2. *The Effects of Vibration on Motor Control*

This field has been explored in depth since 1955 because of its obvious importance to the control of aircraft and spacecraft. It has been reviewed by Grether[78] and by Lewis and Griffin.[79] The measure of motor control in experiments[80-87] has usually been done with a tracking task of some kind, in which the subject uses a control lever to direct a point on an oscilloscope display to pursue a target or to bring the point into some position by compensating for a signal which tends to move the point. The performance at such a task can be compared with performance at the same task in different vibration environments. It is difficult, however, to extract absolute information on motor control from experiments of this kind, as performance may depend strongly on the characteristics and position of the control lever. Lewis and Griffin[88] have shown that the optimum control gain for joystick controls in a vibrating environment was less than in a static one.

The most obvious mechanism by which vibration interferes with motor control is by creating forces which cause the controlling hand to move involuntarily. Torle[85] showed that an armrest will significantly improve tracking performance during simulated buffeting. This is because the arm rest fixes the position of the lower arm relative to the control lever and thus reduces the free inertial mass which the muscles must support against the vibration-induced forces. In a more recent paper, Lewis and Griffin[89] have tried to quantitatively describe the various mechanisms responsible for the degradation in performance with vibration. They found that:

a. directly-transmitted vibration effects were greatest with 4-Hz vertical vibration,

b. there was an error which was uncorrelated with the vibration (i. e., it was apparently not a result of direct mechanical forces) but increased with vibration level and was most obvious at high frequencies, about 64 Hz, and

c. the effects of duration of vibration exposure, up to one hour, could be explained by a simple lack of arousal (boredom).

The presence of an effect of vibration which is more than a simple mechanical effect has been noted by other authors. Carlsöö[75] reviews the history of the phenomenon, and it has been studied recently by researchers in France.[90-92] These investigators have found that, with whole-body exposure to vertical vibration at 18 Hz (which they used to simulate the vibration of a helicopter), there is a loss of kinaesthetic sense, i. e., a loss of the sense of position of the limbs. This effect complicates the task of motor control and may be responsible for the tension and fatigue induced by performing tasks during whole-body vibration.

3.3.3. *The Effects of Vibration on General Performance and Alertness*

"Performance" in experimental conditions involving vibration has often been measured by tasks other than manual control. These tasks involve reaction times[39, 78, 83, 93-96] or choices in which alertness and cognitive abilities take part. It is generally agreed, that only the manual control part of performance tasks are significantly affected by vibration. Wilkinson and Gray[97] studied the effect of vibration duration on performance and could not find a significant effect of fatigue on the performance of a number of tasks, even when the duration was well beyond the "fatigue-decreased proficiency" boundary given by ISO Standard 2631-1978[97] (described below). The question of vibration-induced fatigue still does not have a definite answer.

3.4. *Standards for Human Vibration Exposure*

In the mid 1960's, after the pioneering work of Coermann and his colleagues, it appeared possible to prepare definitive standards for the human tolerance to whole-body vibration. ISO Standard 2631 "Guide for the Evaluation of Human Exposure to Whole Body Vibration"[97] is the result of this effort. The salient features of this standard are graphs showing various tolerance limits as curves of intensity in units of rms acceleration as a function of frequency for sinusoidal vibrations in the vertical and horizontal directions (Figures 4 and 5), and a specification for interpreting the effects of multi-frequency or random vibrations in terms of these curves. The tolerance limits correspond to different durations of exposure and to three conditions, "safe exposure limit", "fatigue-decreased proficiency boundary" and "reduced comfort boundary". As Figures 4 and 5 show, the limits for the different conditions are simple mathematical multiples of each other. The general shape of the curves reflects the resonances discovered by Coermann and his colleagues,[38] and the short-term tolerances found by Magid *et al.*[54] and Temple *et al.*[98] The curves have been reduced to straight lines (on a double-logarithmic graph) for simplicity.

This ISO standard has been criticized,[99] primarily for its specification of time durations corresponding to the various tolerance limits; these durations do not have strong experimental justification. Other authors have examined its specification for evaluating random and multi-frequency vibrations, which were somewhat speculative, and have generally confirmed their value or have proposed improvements.[60, 64] The general acceptance of the ISO guidelines, particularly for the tolerance limit, is probably due to their simplicity of application and the large variability in tolerance to vibration of the human population.

The vibration evaluation standards applicable to vehicles in the Canadian forces is the Air Standardization Coordinating Committee Advisory Publication 61/1 (1977),[100] which specifies methods of vibration exposure evaluation and recommended limits similar to those of ISO 2631.

3.5. *The Vibration Environment in Helicopters*

3.5.1. *Sources of Helicopter Vibration*

There are many sources of vibration in a helicopter. The principal source is the main rotor. In forward flight, the advancing blades of the main rotor move through the air more quickly than the retreating blades on the opposite side. Rotor designs incorporate provisions for allowing each blade to flex backward or forward with respect to its normal position in order to compensate for the variations in lift and drag that occur as it rotates. This flexion of the blades causes significant vibration at the rotational frequency of the rotor, or at the frequency which is the product of the rotational frequency multiplied by the number of blades in the rotor (usually two to four).[101] Additional vibration at this frequency is caused by the buffeting as the rotor blades pass over the helicopter body. In the CH-136 Kiowa, the rotor turns at 354 revolutions per minute and should generate vibrations at 5.9 and 11.8 Hz. The more intense vibration is at 11.8 Hz, which is the blade-passing frequency. The intensity of the vibration in any helicopter will be increased if it is travelling forward at a high speed or if the rotor is exerting a large lifting force.

The tail rotor also generates vibrations, although these are at higher frequencies and are generally less intense in the cockpit.

In piston-engine helicopters, the engine itself is a significant source of vibration and noise. In turbine-driven helicopters, such as the Kiowa, the engine is primarily a source of high-frequency noise rather than of vibration.

The helicopter, like all aircraft, is subject to vibrations created by wind buffeting. In flight, it will exhibit low-frequency motions in response to the pilot's operation of the controls; this is especially evident when the helicopter is hovering.

3.5.2. *The Intensity of Helicopter Vibration*

Measurements of the vibration levels in many military helicopters have been made. Johnson and Priser[102] have reviewed measurements made of vibration in United States Army helicopters. Their review does not contain data on the Kiowa helicopter, although they mention that measurements of vibration levels in the cockpit have been performed. Griffin[76] has published vibration spectra for the British Army "Scout" helicopter. Delahaye and Auffret[2] state that the French have measured helicopter vibration and give some results.

Johnson and Priser[102] point out the difficulty of assessing measurements of vibration intensity. Some measurements have been made on the seat frame; others on the seat cushion directly beneath the pilot's buttocks. The latter method is a better measure of the vibration to which the pilot is exposed, but it may be affected by the pilot's own anthropometry and weight. Many measurements taken before ISO Standard 2631 was published are difficult to compare with the Standard because of the lack of data on the measurement techniques. Griffin[76] compares his data on the Scout helicopter with the ISO Standard and his graphs show that at two frequencies the vertical vibration exceeds the "8 Hour Fatigue-Decreased Proficiency" level. Nowhere does the vibration exceed the "1-Hour Fatigue-Decreased Proficiency" level or 0.2 g rms intensity. Griffin's measurements were made at the cockpit floor.

Rance and Chappelow[5] and Delahaye and Auffret[2] report on surveys of helicopter aircrew in which an effort was made to assess the subjective effects of vibration. Pilots were inclined to rate some helicopters worse than others because of vibration, and did report discomfort and difficulty reading displays when they were fatigued. The French and British Forces have used a rating scale for helicopter vibration which is based on the subjective assessment of pilots, and, according to Delahaye *et al.*,[2] the results are "remarkably consistent."

4. *SOLUTIONS TO THE PROBLEM OF BACKACHE IN HELICOPTER AIRCREW*

Potential solutions to the problem of helicopter aircrew discomfort have been proposed and implemented by several authorities.[2, 6, 7, 31, 103] Solutions may be divided roughly into those which involve the design of the helicopter, those which involve the selection and training of the pilot and those which involve the interface between the pilot and the helicopter, that is, the seat and controls. Solutions may also be divided into "quick fixes"; that is, immediately-effective solutions that may be only partially effective, such as seat cushions, or long-term solutions which may be far more effective, but cannot be implemented until the current stock of helicopters is replaced by new aircraft now being designed.

4.1. *Modifications to the Design of the Helicopter*

Changes in the design of the helicopters used by the Armed Forces will tend to reduce the backache problem if they tend in the following directions:

a. Reduction in the vibration of the cockpit.

b. Improvement in the stability of the helicopter, making it easier to fly.

c. Adapting the cockpit space to suit the anthropometry of the aircrew population.

It is obvious that these are long-term solutions, and cannot be implemented until new helicopters are acquired. However, the specifications for these helicopters should reflect some of these objectives by now.

4.1.1. *Vibration Reduction*

The reduction of vibration in helicopters is an engineering problem whose solution is actively pursued by designers.[101] The United States Air Force has a standard for the vibration level in helicopters (USAF Mil A 8892, cit. by Knoche and Schulte-Wintrop[7]).

The experiment performed by Shanahan and Reading[74] described in Section 3.2 shows that helicopter vibration may not be the principal cause of the pilot's back discomfort.

One can conclude that vibration, in itself, is not a serious problem in the present generation of helicopters. It is the combination of vibration with exacting visual and manual performance requirements placed on aircrew which causes the problems. Because of this, it should be considered desirable, although not mandatory, to reduce the vibration level in helicopters.

4.1.2. *Stability Improvement*

There are efforts by a number of investigators[104-106] toward improving the effective stability of the helicopter, thereby making it easier to fly. These involve the use of computers to maintain the helicopter's stability through feedback systems, and to augment the pilot's control actions through servo-systems.

The use of computers and electronics in helicopter control systems creates a number of opportunities, and a commensurate number of problems. The designer of the helicopter is now free to use whatever control device is most appropriate for the pilot, rather than being limited to the mechanical-hydraulic collective, cyclic and pedal controls. Experimental evaluation of systems using manually-operated joysticks is being conducted.[106] Since the use of these control systems allows the designer to place them in more convenient locations, the development of such systems permits the helicopter operator to assume a more relaxed posture at the controls. Indeed, these design changes may solve the backache problem by themselves.

The new U. S. Army Apache helicopter incorporates a computer and sensors which augment the stability of the aircraft. However, the standard controls (cyclic, collective and pedals) are still used. One reporter states that the Apache is significantly easier to fly, particularly in hovering.[107]

It will be interesting to see whether or not these modifications result in changes in the level of backache experienced by the pilots of this aircraft.

4.1.3. *Cockpit Space*

Another factor in the problem of backache is the design of the cockpit. The interior should have enough space to accommodate the majority of potential pilots in such a way that they can sit in an upright posture and reach the controls without difficulty. Because of the variety in human dimensions, there should be provision to adjust the seat in the vertical and horizontal directions to allow all personnel to reach the controls and see the visual displays comfortably.

These obvious requirements are not met in the Kiowa helicopter. It is not difficult to understand why such a situation has arisen. The Kiowa is a military adaptation of a helicopter designed for general use. The adaptation has included provision for armour-plate beside and beneath the pilot seat. The Kiowa seat is not adjustable, thus, pilots whose leg lengths or seated heights are far different from the average find it inconvenient to reach the controls. In addition, military pilots wear a flight helmet with a visor shield above the helmet surface; with this equipment, pilots with a seated height of more than 96 cm[108] cannot sit upright in the Kiowa seat.

It is to be hoped that, in the basic design of future helicopters, the special requirements of military operations should be considered and adequate space provided. At the very minimum, seats should be adjustable to accommodate pilots whose critical dimensions fall between the 5 th and 95th percentiles of the potential aircrew population. The design of the seat, controls and interior space must account for the use of additional protective gear, not only flight helmets but also survival packs, chemical defence clothing and other devices.

4.2. *Solutions Involving the Helicopter Pilot*

The surveys cited in Sub-Section 1.2 show that not all helicopter pilots suffer from backache. Therefore, an individual may have characteristics which make it more likely that he or she may suffer from low-back pain as a result of helicopter aircrew duties. Some personal characteristics, such as general fitness and strength, can be changed through training. Others, such as anthropometry and the configuration of the lower spine, cannot be changed, but could be eliminated from the helicopter pilot population by the screening of applicants for training.

4.2.1. *Screening of Pilot Training Candidates*

One approach to the reduction of low-back pain among helicopter pilots is to add new tests and criteria for acceptance to the medical qualification procedure for candidates for flying training. Two obvious factors which can be tested are general anthropometry and the configuration of the lower spine.

4.2.1.1. *Screening for Predisposition to Backache*

Certain authorities have recommended a stricter approach to screening pilot candidates for susceptibility to backache. Delahaye and Auffret[31] describe the rigourous screening procedures used by the French Air Force in Chapter 7 of their book. They routinely perform X-ray examinations of all candidates for flying training. (X-rays are not routinely used in the corresponding examinations in Canada, the United Kingdom or the United States of America.) On the basis of the X-rays, several measurements are taken of the spine to determine the degree of spinal scoliosis, abnormal kyphosis of the thoracic spine and the geometry of the lumbo-sacral junction. It should be remembered that, prior to the X-ray examinations, a complete history and general physical examination is taken. Any candidate with a history, symptoms or signs of spinal malformation or disease would be disqualified, as would be the case in other armed forces.

Delahaye and Auffret[31] recommend the disqualification of candidates with certain spinal conditions, even when the candidates have no overt symptoms, pain or disability. What is more interesting is that, in certain conditions, they would disqualify a candidate for helicopter aircrew training, but consider him (or her) fit for training as a combat or transport aircraft pilot.

Candidates with anomalous vertebrae at the transition between the lumbar vertebrae and the sacrum form one major group of these cases. (This condition, which is quite common, is called lumbarization of the first sacral vertebra or sacralization of the fifth lumbar vertebra.) Delahaye and Auffret recommend that, when the "pivot vertebra" (that is, the lowest free vertebra not fused into the sacrum) is clearly above the iliac crest, or forms abnormal or asymetrical articulations with the ilium, the candidate should be disqualified as a helicopter pilot, but not as a pilot for combat or transport aircraft. If the asymmetry of the articulations with the ilium were extreme, or if there were any associated symptoms, the candidate would be disqualified altogether. They report that about 30% to 50% of patients with low-back pain show some form of this abnormality.

Other cases in which the candidate would be disqualified only as a helicopter pilot are spondylolisthesis, with less than 1-cm slippage of the fifth lumbar vertebra relative to the sacrum; and moderate sequelae of osteochondrosis of growth in the lumbar region.

There are several reasons why these grounds for disqualification may appear arbitrary and unjustified. The relationship between backache and any particular condition of the lumbar spine is not clear. Reports of surveys of healthy volunteers for impact research programmes,[109, 110] reveal that congenital abnormalities of the spine are very common among apparently healthy, symptom-free, young male adults.

The important question concerning these conditions is: Do they increase the likelihood of the development of chronic or disabling back pain during helicopter flight duties? This question may only be answered through the detailed screening of pilot candidates coupled with the continued follow-up of the spinal health of the successful candidates through their careers. Kazarian and Belk[111] have recommended X-rays as part of the screening of candidates for training as high performance fighter pilots. A pilot study of the ability of X-ray examinations to detect spinal abnormalities and the correlation of these abnormalities with backache will help decide on the value of such examinations.

4.2.1.2. *Anthropometric Screening*

If helicopters without adequate cabin space or pilot-seat adjustments continue to be used, there may be some advantage in eliminating those pilot candidates who would be expected to have difficulty assuming a normal posture in the cabin because of their physical dimensions. Cressman[108] has shown that the Kiowa helicopter prevents a large fraction of the adult male population from sitting comfortably while operating the controls.

It is unlikely that a proposal of this kind would be welcomed, because

a. not all helicopters in the CF share the same problems, and

b. selection on the basis of physical size may cause the rejection of candidates who are well-qualified for other reasons.

However, candidates for pilot training should be informed of the potential problems created by their anthropometry. Some may be induced to choose careers in which they have less risk of discomfort.

4.2.3. *Physical Training of Pilots*

The role of the abdominal muscles in relieving the stresses on the spine caused by lifting has been described before. Descriptions of "typical" patients of low-back pain often refer to the patient's generally poor physical condition and excessive weight. For these reasons, it is strongly suggested that exercises which strengthen the muscles of the abdomen and lower back may relieve

the symptoms of backache, and these exercises are often recommended as part of therapeutic programmes.[112] Delahaye and Auffret[2] (p. 255) recommend that helicopter pilots participate in a regular exercise programme consisting, in particular, of exercises which strengthen the muscles which reinforce the spine.

The prophylactic value of such exercises for helicopter pilots is not proven, but a consideration of their therapeutic value and common sense suggest that they should be performed by all helicopter pilots. It is also important that pilots are not overweight, as excessive weight can only increase the stress on the lumbar spine.

There is now a growing body of literature on the value of education in the treatment of back pain.[112, 113] The education not only comprises the exercises needed to strengthen the muscles supporting the trunk, but also the best postures to maintain during normal activities in order to reduce the stresses on the lumbar spine. "Back Schools" have been developed in several centres, including Toronto, Canada. Although they are primarily attended by patients of spinal disease or those with past episodes of acute back pain, it has been suggested that the content of the schools be made part of the general educational curriculum, in order to reduce the incidence of backache in the population.[112] The value of back school in the treatment of chronic pain has been quite convincingly demonstrated.[113] The prophylactic value of back school has not yet been tested (to the author's knowledge) but should be at least as great as its therapeutic value.

Education programmes based on the "Back School" concept could easily be carried out at each Canadian Forces base by the Flight Surgeon in charge of each squadron.

4.3. *Modifications to the Helicopter Seat and Controls*

Some aspects of the design of the seat and controls of the helicopter have been described in Section 4.1 above, in particular, the improvement of the stability of the machine and the space available in the cabin for adequate seating.

4.3.1. *Helicopter Seats*

Helicopter seats must meet several design objectives, including:

a. crashworthiness (see, for example, Volume IV of the Aircraft Crash Survival Design Guide[114]),

b. low weight,

c. adjustability, and

d. vibration isolation.

These objectives may create conflicting requirements for the designer. It would be desirable to undertake an international research and development effort to create helicopter seats which meet all of these objectives effectively. There may be additional requirements, such as the inclusion of armor plate or survival packs in the seat structure.

Delahaye and Auffret[2] criticize existing seats used by the French armed forces for being narrow, and failing to extend far enough forward. They suggest that seats be adjustable in height, forward and backward position and in the rake of the seat back. They also suggest the development of an anthropometric programme towards defining the ideal range of adjustment for a helicopter seat. They describe research towards the development of improved vibration isolation in helicopter seats through the use of different cushions. Poirier[115] has studied the vibration transmission properties of different foam formulations in a helicopter seat.

One major question in designing the seat of the helicopter is whether or not the pilot will be able to use the support provided by the seat back while operating the controls. Several authorities have mentioned the value of lumbar support for the helicopter pilot,[4, 7, 103] and it is the personal observation of the author that the posture of at least *some* pilots makes the provision of lumbar support valuable and feasible. This is based on the fact that the "helicopter hunch" of

these pilots is a posture with an almost vertical line between the pelvis and the shoulders, but also with the pelvis and shoulders rotated so that the normal lumbar lordosis is absent. Other pilots may lean forward slightly while operating the cyclic, and, for them, the provision of lumbar support may be of limited value. Steele-Perkins[105] reports that United Kingdom pilots of the Lynx helicopter were offered a back cushion with a fixed lumbar support but many did not like it.

Pilots in the CF who have been using the Kiowa helicopter have made use of seat pads and lumbar-support cushions, some of which are "custom-made" by their respective base safety-systems techniciana. Some of these cushions enable shorter pilots to overcome the lack of adjustment in the Kiowa seat, and assume a more forward seating-position, which allows them to operate the cyclic without an exaggerated forward leaning. The direct lumbar support provided by these cushions is only secondary to the change in posture they allow. There is a danger that these "jury-rigged" solutions to postural problems may adversely affect the performance of the seat as a vibration isolation system or compromise the safety of restraint systems.

A seat pad on the seat below the pelvis will change the angle that the pilot's legs must assume in operating the pedals; this, in turn, may allow a more natural pelvis angle and a more natural curvature of the lumbar spine.

It is doubtful, that a seat back which is raked backward at a comfortable angle will offer much advantage if the controls of the helicopter do not permit the pilot to lean backward into the seat. Even if this is the case, a backward-raked seat back may cause more of the helicopter's vibration to be transmitted to the shoulders and head. The transmission of vibration to the shoulders and head may interfere with vision or precise movements of the upper arms. It is, of course, possible that a seat may attenuate vibrations delivered by the seat back to the point where they would not be a problem.

Steele-Perkins (personal communication) reports that a contoured seat pan (actually, a personal survival pack) can prevent pelvic tilt and increase lumbar lordosis in the sitting position.

The influence of seat backs and restraints on control performance during exposure to vertical vibration is an area for further research. Some of the best studies of control performance during vibration exposure have been performed with the subjects sitting on a seat without any back support.[89]

4.3.2. *Helicopter Controls*

The controls of the helicopter have been identified by many authorities as the area in which there is the greatest possibility of relieving the discomfort of the pilot.

Approaches to changing the controls exist at three levels. The simplest, and most limited, approach is to modify the geometry of the controls on existing helicopters, so that they can be operated by aircrew from a more comfortable position. Cressman[108] proposes such a modification to the controls of the Kiowa. Although such modifications may enable more pilots to use the controls, they are not likely to reduce the problem of backache.

At the second level, the controls for future helicopters can be designed on the same principles as current controls, but with better geometry, as proposed by Cobientz *et al.*[118] This approach should enable a larger fraction of the total aircrew population to use the controls effectively. However, it would not change the basic posture of the pilot, except for the fact that he or she may not have to lean sideways to operate the collective lever. The requirement that the elbow should rest on the thigh would remain, and this would dictate an uncomfortable position for the spine.

The advantage of retaining controls of the present design is that pilots and design engineers would not have to contend with the difficulties and decisions involved in a re-design of the helicopter control system.

The third approach to modifying the helicopter controls in order to relieve the backache problem would be to redesign the controls entirely. This approach has been mentioned earlier in Sub-Section 4.2 in connection with making the helicopter easier to fly. Obviously, the use of the

computer to stabilize the helicopter, permits, as a side-benefit, a free choice in the design of the electronic controls which provide input to the computer. The position and range of movement of the controls can be optimized in order to permit the pilot to operate them precisely from a relaxed position in the seat.

An alternative approach would be to redesign the position and range of movement of the mechanical-hydraulic controls of the helicopter. The position of the cyclic and collective levers in current helicopters have a certain relationship to their function, which allows an "intuitive" understanding of how to use them. However, they do not make the best use of the human body's ability to make fine control movements, nor do they permit the use of supports for the pilot's arms, so that these movements can be done easily and the hands are isolated from gross movements of the body and vibration. It may be possible to define, by human engineering studies, an optimum geometry for control levers and arm rests which would permit full control of the helicopter through precise movements of the wrist and fingers, without dictating the posture assumed by the rest of the body.

The difficulty of any such modification is that, once having abandoned a "conventional" control geometry, one must prove that the new controls offer significant improvements over the old. This requires extensive human engineering research into such questions as:

a. What is the optimum position for each control?

b. What is the optimum control gain for each control? The answer to this question obviously must take into account the effects of vibration on control dynamics, and the characteristics of stability of the aircraft.

c. How will the modified controls affect the workload, tension and performance of the pilot?

d. How will the modified controls affect the ability of pilots to learn helicopter operation?

Research into these questions is already proceeding;[104-106] but more research and practical demonstrations of the new controls will be necessary before they are generally accepted.

4.4. *Other Factors*

This essay has dealt primarily with the *biodynamic* factors believed to be causes for the discomfort of helicopter pilots. *The principal factors are vibration and posture.* The postural problem, which appears to be most significant, is related to the stability and flight dynamics of the helicopter and the design of the seat and controls.

There are many other factors which contribute to the difficulty of flying a helicopter, and these may contribute indirectly, through psychological tension and stress, to the backache problem. Such factors as the visibility of displays, heat stress, the special stresses of having to maneuver an aircraft close to the ground in tight quarters, and flying at night with special night-vision goggles pose problems which are unique to the operation of the helicopter. Good biodynamic design and human engineering can alleviate the physical discomforts of helicopter pilots. However, it is unrealistic to expect that flying a helicopter will be entirely without stress, particularly in the military environment.

4.5. *Research Areas Related to Helicopter Aircrew Discomfort*

The various areas of research have been mentioned above in connection with possible solutions to the backache problem. Each of the potential solutions identified above has corresponding questions; in particular, how effective it will be and how costly in terms of the other demands on helicopter aircrew. It is obvious that several areas of research must be considered.

4.5.1. *Causes of Backache*

Although there are several promising hypotheses, it cannot be said for certain that the causes of backache have been specifically identified. Further work in epidemiology and biomechanics are needed to clarify the relation between the working environment, posture and lumbar spinal disease. Equally uncertain is the relation between the geometry of the spine and backache. There will have to be more research before it can be said for certain that a screening programme can identify in advance those individuals predisposed to backache.

Further research should be carried out on the value of exercise programmes and training, as in the "Back Schools" described above in preventing acute or chronic backache.

Although there is evidence from several sources[12, 15, 19, 75, 117] that working environments in which humans are exposed to vibration are correlated with back pain, the relationship between pain, spinal disease and vibration exposure is not clear. The posture of those exposed to vibration may be a large contributing factor to their problems.

4.5.2. *Human Factors in Helicopter Operation*

It is possible that altering the controls of the helicopter will greatly alleviate the discomfort of the pilot. However, research is needed, not only to evaluate the degree of potential relief provided by an alteration, but also to evaluate how it may affect the controllability of the helicopter.

There has been much basic research on human performance at manual control tasks, both during vibration and otherwise. This research is being extended to assist the design of the helicopter controls through modelling of the operator as part of the control system. But many questions remain.

a. How will the altered posture afforded by side-arm controls affect the response of the pilot to vibration? The use of the seat back may increase the transmission of vibration to the head,[51] and thus affect vision and control; alternatively, it may reduce the response to low-frequency translational vibration and make the control task easier.

b. What is the optimum control system for a helicopter? Individual questions about this subject were listed above in Sub-Section 4.4. The solution may require studies of performance at simple tracking tasks using various control geometries in vibrating environments.

c. How much relief from discomfort can be expected from new control and seating geometries? The new systems may go far to relieve the tension associated with helicopter operation, but they will not eliminate the need for vigilance and precise control, nor will they change the basic hazards and distractions of the cockpit environment. It still may be necessary to limit the time spent by an individual pilot in a helicopter in order to prevent chronic discomfort and reduced efficiency.

4.5.3. *DCIEM and the Helicopter Backache Problem*

The response of DCIEM to the backache problem can take several forms. At one extreme, DCIEM may study the problem and recommend solutions for the CF only. After objectively determining the scale and seriousness of the backache problem among CF aircrew, specific recommendations based on developments in other countries may be proposed, implemented and evaluated. These would include:

a. cushions or back braces to be installed on existing CF helicopters,

b. screening of CF aircrew candidates for predisposition to backache,

c. regulating the time CF aircrew spend in helicopters (this is already done to some extent),

d. development of training courses and exercise regimens as prophylaxis against backache, and

e. publicizing the availability of the above remedial measures among CF aircrew.

The above steps may be taken as part of a research programme which would evaluate their effectiveness. Close liaison with aircrew and base medical officers would be required. Prospective studies of backache take a long time and a large sample, so there would have to be a long-term commitment to the planned course of action by the Department of Defence. DCIEM does have expertise in the development of physical fitness standards and training methods which could be of value here.

An important difficulty with any evaluation experiment is the requirement for the random selection of experimental and control subjects, and the possible requirements for secrecy in order to prevent the results from being influenced by prejudices or expectations. This may make the objective evaluation of remedial measures impossible.

At the other extreme, the problems of helicopter aircrew can be viewed as an international problem which is amenable to an international effort towards a solution. The contribution made by DCIEM would be to contribute, through basic research on the general problems of helicopter seating, anthropometry, workload and controls to a future definitive solution. Some approaches would be:

a. to conduct research into the effects of buffeting and vibration on manual control using "helicopter-like" controls with various postures. One possibility is the use of an arm-rest of some form for the right arm which would reduce the "slouch" posture required to operate the cyclic control.

b. to conduct research into the human ability to use posture to counteract the effects of vibration and buffeting. Although it would be difficult and unethical to simulate low-back pain in humans through vibration exposure, indirect means of assessing the load on the spine, such as abdominal pressure or myoelectric measurements of back-muscle activity[118] may be used to determine how the loads on the spine change during the response to vibration or during various efforts to reduce vibration transmission to the hands or head.

c. to conduct research, in co-operation with the designers of helicopter stability-augmentation systems, into the optimal characteristics of side-arm or similar controls.

d. to conduct research into the ability of different seat designs to alleviate stresses on the spine induced by vibration and reduce the transmission of vibration to the head and hands.

e. to conduct anthropometric surveys and experiments in order to assist in the development of standards for the size of helicopter cockpit interior spaces, and the range of adjustment of seats and controls.

DCIEM does have some expertise in the fields of human performance assessment using tracking or vigilance tasks. A motion simulator at the nearby University of Toronto Institute for Aerospace Studies can be used to simulate the low-frequency components of helicopter motion, those due to buffeting and control actions. It is not capable of reproducing vibrations at frequencies higher than 10 Hz with any accuracy, therefore the vibration caused by the rotor of a helicopter cannot be simulated.

However, it would be useful simply to simulate the low-frequency components of helicopter motion because these complicate the control task, which, in turn, determines the posture of the pilot. This posture, and the associated stresses, is the more important factor in the generation of backache.

Experiments using higher-frequency vibrations may be conducted in co-operation with other laboratories, such as the Laboratoire de Médecine Aérospatiale du Centre d'Essais en Vol at Brétigny sur Orge in France or the Aerospace Medical Research Laboratories at Wright-Patterson Air Force Base in the United States which have the required vibration equipment.

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6. *REFERENCES*

1. SKJENNA, O. W. ***Cause Factor: Human - A Treatise on Rotary Wing Human Factors.*** Health and Welfare Canada, Ottawa, Canada, 1981.

2. DELAHAYE, R. P., R. AUFFRET, P. J. METGES, J. L. POIRIER and B. VETTES. Ch. 6: Backache in Helicopter Pilots. ***Physiopathology and Pathology of Spinal Injuries in Aerospace Medicine (2nd Ed.)***, R. P. DELAHAYE and R. AUFFRET (eds.), AGARD, Neuilly-Sur-Seine, France, 211-263, 1982. (translated by P. Howard for the Aerospace Medical Panel, AGARD, from the French original of 1980).

3. HURT, JR., H. H. ***Aerodynamics for Naval Aviators.*** University of Southern California, Los Angeles, 1965.

4. GOEDE, R. Backache in Helicopter Pilots. Flight Comment No. 4:16-19, 1977.

5. RANCE, B. H. and J. W. CHAPPELOW. Aircrew Assessment of the Vibration Environment in Helicopters. ***AGARD Conference Proceedings No. 145: on Vibration and Combined Stresses in Advanced Systems***, H. E. VON GIERKE (ed.), AGARD, Neuilly-sur-Seine, France, B1-1 to B1-7, 1975. (Papers presented at the Aerospace Medical Panel Specialists' Meeting, held at Oslo, Norway, 22-23 April 1974).

6. READER, D. C. Some Improvements To The UK Helicopter Cockpit. ***AGARD CP-255: Operational Helicopter Aviation Medicine***, S. C. KNAPP (ed.), AGARD, Neuilly-sur-Seine, France, 60-1 to 60-3, 1978.

7. SCHULTE-WINTROP, H. C. and H. KNOCHE. Backache in UH-1D Helicopter crews. ***AGARD Conference Proceedings No. 255: Operational Helicopter Aviation Medicine***, S. C. KNAPP (ed.), AGARD, Neuilly-sur-Seine, France, 19-1 to 19-11, 1978. (Paper presented at the Aerospace Medical Panel's Specialists' Meeting held at Fort Rucker, Alabama, USA, 1-5 May 1978.).

8. ROTONDO, G. Workload and Operational Fatigue in Helicopter Pilots. Aviat. Space Environ. Med. 49:430-436, 1978.

9. MATVEEV, I. G. and I. N. KAMENSKI'I. (Physiologic and Hygenic Evaluation of the Vibrations in a Transport Helicopter Cockpit). Kosm. Biol. Avaikosm. Med. 15:22-25, 1981. (in Russian).

10. FROOM, P., J. FROOM, D. V. DYK, Y. CAINE, J. RIBAK, S. MARGALIOT and Y. FLOMAN. Lytic Spondylolisthesis in Helicopter Pilots. Aviat. Space Environ. Med. 55:556-557, 1984.

11. SANDOVER, J. Vibration, Posture and Low-Back Disorders of Professional Drivers. Report No. DHS 402, University of Technology, Loughborough, England, 1981.

12. MILBY, T. H. and R. C. SPEAR. Relationship Between Whole Body Vibration and Morbidity Patterns Among Heavy Equipment Operaters. Publication No. (NIOSH) 74-131, Department of Health, Education and Welfare, Washington, DC, U. S. A., 1974.

13. GRUBER, G. J. and H. H. ZIPERMAN. Relationship Between Whole Body Vibration and Morbidity Patterns Among Motor Coach Operators. Publication No. 75-104, Department of Health, Education and Welfare, Washington, DC, U. S. A., 1975.

14. GRUBER, G. J. Relationships Between Whole Body Vibration and Morbidity Patterns Among Interstate Truck Drivers. Publication No. 77-167. Department of Health, Education and Welfare, Washington, DC, U. S. A., 1977.

15. TROUP, J. D. G. Driver's Back Pain and its Prevention: A Review of the Postural, Vibratory and Muscular Factors, together with the Problem of Transmitted Road Shock. Applied Ergonomics 9:207-214, 1978.

16. HILL, M., K. WOODCOCK, D. BEEVIS and H. MACDONALD. A Study Into the Incidence and Causes of Lower Back Pain Among M113 APC Drivers at CFB Gagetown. Report No. 79-R-24, Defence and Civil Institute of Environmental Medicine, Toronto, Canada, 1979.

17. ROSEGGER, R. and R. G. ROSEGGER. Health Effects of Tractor Driving. J. Agricultural Engineering Res. 5:241-275, 1960.

18. ANDERSSON, G. B. Epidemiologic Aspects on Low-Back Pain in Industry. Spine 6:53-60, 1981.

19. FRYMOWER, J. W. and M. H. POPE. The Role of Trauma in Low Back Pain: A Review. J. Trauma 18:628-634, 1978.

20. SPEAR, R. C., C. KELLER, V. BEHRENS, M. HUDES and D. TARTER. Morbidity Patterns Among Heavy Equipment Operators Exposed to Whole Body Vibration - 1975. Followup to a 1974 Study. Publication No. 77-120, Department of Health, Education and Welfare, Washington, DC, U. S. A., 1976.

21. FINNESON, B. E. Anatomy of the Low Back. *Low Back Pain*, B. E. FINNESON (ed.), J. B. Lippincott Co., Philadelphia, PA, U. S. A., 1-26, 1980.

22. KLEITZ, C. and R. P. DELAHAYE. Ch. 2: Anatomy of the Spine. *Physiopathology and Pathology of Spinal Injuries in Aerospace Medicine*, AGARD, Neuilly-sur-Seine, France, 9-28, 1982.

23. KING, A. I. Bioengineering Measurement. Report No. N00014-75-C-0372, Dept. of the Navy, Office of Naval Research, Biophysics Program, Code 144, 1977. (85 pages).

24. LORENZ, M., A. PATWARDHAN and R. VANDERBY, JR. Load-Bearing Characteristics of Lumbar Facets in Normal and Surgically Altered Spinal Segments. Spine 8:122-130, 1983.

25. MORRIS, J. M. Biomechanics of the Lumbar Spine. *Low Back Pain, Second Edition*, B. E. FINNESON (ed.), J. B. Lippincott Company, Philadelphia, PA, U. S. A., 27-44, 1980.

26. KAZARIAN, L. E. Creep Characteristics of the Human Spinal Column. Orthopaedic Clinics of North America 6:3-22, 1975.

27. NACHEMSON, A. L. and J. M. MORRIS. *In Vivo* Measurements of Intradiscal Pressure. J. Bone and Joint Surgery 46-A:1077-1092, 1964.

28. NACHEMSON, A. L. Disc Pressure Measurements. Spine 6:93-97, 1981.

29. FINNESON, B. E. *Low Back Pain, Second Edition*. J. B. Lippincott Company, Philadelphia, PA, U. S. A., 1980.

30. NACHEMSON, A. L. The Lumbar Spine. An Orthopaedic Challenge. Spine 1:59-71, 1976.

31. DELAHAYE, R. P., R. AUFFRET, G. LEGUAY, P. DOURY, P. J. METGES and C. KLEITZ. Ch. 7: The Spine and Fitness for Flight. *Physiopathology and Pathology of Spinal Injuries in Aerospace Medicine*, AGARD, Neuilly-sur-Seine, France, 264-300, 1982. (Translated from the French original by P. Howard).

32. COLE, S. H. The Effects of Noise and Vibration Upon Human Performance: Implications For the Operation of Military Systems. *DRG Seminar: The Human As A Limiting Element In Military Systems*, Defence and Civil Institute of Environmental Medicine, Toronto, Canada, 13:1-18, 1983.

33. GUIGNARD, J. C. Ch. 29: Vibration. *A Textbook of Aviation Physiology*, J. A. GILLIES (ed.), Pergamon, Oxford, U. K., 1965.

34. HORNICK, R. J. Ch. 7: Vibration. *Bioastronautics Data Book*, J. F. PARKER and V. R. WEST (eds.), National Aeronautics and Space Administration, Washington, DC, U. S. A., 297-348, 1973.

35. LINDER, G. S. Mechanical Vibration Effects on Human Beings. Aerospace Med. 33:939-950, 1962.

36. SHARP, G. R. Ch. 14: Vibration. *Aviation Medicine*, vol. 1 , G. DHENIN and J. ERNSTING (eds.), Tri-Med Books Ltd., London, England, 278-294, 1978.

37. VON GIERKE, H. E. and N. E. CLARKE. Effects of Vibration and Buffeting on man. *Aerospace Medicine*, H. W. RANDEL (ed.), Williams and Wilkins, Baltimore MD, U. S. A.,

198-223, 1971.

38. CLARK, W. S., K. O. LANGE and R. R. COERMANN. Deformation of the human body due to uni-directional forced sinusoidal vibration. Human Factors 4:255-274, 1962.

39. HORNICK, R. J., C. A. BOETTCHER and A. K. SIMONS. The Effect of Low Frequency, High Amplitude, Whole Body, Longitudinal and Transverse Vibration Upon Human Performance. Final Report Contract No. DA-11-022-509-ORD-3300, Bostrom Research Laboratories, Milwaukee, Wisconsin, 1961.

40. ALLEN, G. Part I: the Use of a Spinal Analogue to Compare Human Tolerance of Repeated Shocks with Tolerance of Vibration. *AGARD CP-253: Models and Analogues for the Evaluation of Human Biodynamic Response, Performance and Protection*, H. E. VON GIERKE (ed.), AGARD, Neuilly-sur-Seine, A24-1 to A24-4, 1978.

41. GRIFFIN, M. J., C. H. LEWIS, K. C. PARSONS and E. M. WHITHAM. The Biodynamic Response of the Human Body and its Application to Standards. *AGARD Conference Proceedings no. 253: Models and Analogues for the Evaluation of Human Biodynamic Response, Performance and Protection*, H. E. VON GIERKE (ed.), AGARD, Neuilly-sur-Seine, France, A28-1 to A28-18, 1978.

42. LANGE, W. Zur Beurteilung von Schwingungsgemischen, die uber die Sitzflache auf den Menschen Einwirken. European Journal of Applied Physiology 33:151-170, 1974.

43. ZECHMAN, F. W., D. PECK and E. LUCE. Effect of vertical vibration on respiratory airflow and transpulmonary pressure. J. Appl. Physiol. 20:849-854, 1965.

44. DIXON, M. E., P. B. STEWARD, F. C. MILLS, C. J. VARVIS and D. V. BATES. Respiratory Consequences of Passive Body Movement. J. Appl. Physiol. 16:30-34, 1961.

45. GAEUMAN, J. V., G. N. HOOVER and W. E. ASHE. Oxygen Consumption During Human Vibration Exposure. Aerospace Med. 33:469-474, 1962.

46. HOOVER, G. N. and W. E. ASHE. Respiratory Response to Whole-Body Vertical Vibration. Aerospace Med. 33:980-984, 1962.

47. GUIGNARD, J. C. Ch. 5: Physiological Effects of Vibration. *Aeromedical Aspects of Vibration and Noise*, J. C. GUIGNARD and P. F. KING (eds.), AGARD, Neuilly-sur-Seine, France, 36-45, 1972.

48. DUFFNER, L. R., L. H. HAMILTON and M. A. SCHMITZ. Effect of Whole-Body Vertical Vibration on Respiration in Human Subjects. J. Appl. Physiol. 17:913-916, 1962.

49. SHARP, G. R., G. A. PATRICK and W. R. WITHEY. The Respiratory and Metabolic Effects of Constant Amplitude Whole-Body Vibration in Man. *AGARD CP-145: Vibration and Combined Stresses in Advanced Systems*, H. E. VON GIERKE (ed.), AGARD, Neuilly-sur-Seine, France, B15-1 to B15-6, 1975.

50. GRIFFIN, M. J. Vertical Vibration of Seated Subjects: Effects of Posture, Vibration Level, and Frequency. Aviat. Space Environ. Med. 46:269-276, 1975.

51. ROWLANDS, G. F. The Transmission of Vertical Vibration to the Heads and Shoulders of Seated Men. Technical Report 77068, Royal Aircraft Establishment, 1977.

52. OBORNE, D. J. and P. A. BOARER. Subjective Response to Whole-Body Vibration. The Effects of Posture. Ergonomics 25:673-681, 1982.

53. GUIGNARD, J. C. Ch. 6: Psychological Effects of Vibration. *Aeromedical Effects of Vibration and Noise*, J. C. GUIGNARD and P. F. KING (eds.), AGARD, Neuilly-sur-Seine, France, 46-66, 1972.

54. MAGID, E. B., R. R. COERMANN and G. H. ZIEGENRUECKER. Human Tolerance to Whole-Body Sinusoidal Vibration: Short-Time, One-Minute and Three-Minute Studies. Aerospace Med. 31:915-924, 1960.

55. MIWA, T. Evaluation Methods for Vibration Effect. Part 1: Measurements of Threshold and Equal Sensation Contours of Whole Body for Vertical and Horizontal Vibrations.

Ind. Health 5:183-205, 1967.

56. JONES, A. J. and D. J. SAUNDERS. Equal Comfort Contours for Whole-Body Vertical Pulsed Sinusoidal Vibration. J. Sound and Vibration 23:1-14, 1972.

57. SHOENBERGER, R. W. and C. S. HARRIS. Psychophysical Assessment of Whole-Body Vibration. Human Factors 13:41-50, 1971.

58. DONATI, P., A. GROSJEAN, P. MISTROT and L. ROURE. The Subjective Equivalence of Sinusoidal and Random Whole-Body Vibration in the Sitting Position (An Experimental Study Using the 'Floating Reference Vibration' Method). Ergonomics 26:251-274, 1983.

59. GRIFFIN, M. J. Subjective Equivalence of Sinusoidal and Random Whole-Body Vibration. J. Acoustical Society of America 60:1140-1145, 1976.

60. SHOENBERGER, R. W. Comparison of the Subjective Intensity of Sinusoidal, Multifrequency, and Random Whole-Body Vibration. Aviat. Space Environ. Med. 47:856-862, 1976.

61. PARSONS, K. C. and M. J. GRIFFIN. Vibration and Comfort. II. Rotational Seat Vibration. Ergonomics 25:631-644, 1982.

62. LEATHERWOOD, J. D., T. K. DEMPSEY and S. A. CLEVENSON. An Experimental Study for Determining Human Discomfort Response to Roll Vibration. TN D-82-66, National Aeronautics and Space Administration, 1976.

63. PARSONS, K. C. and M. J. GRIFFIN. The Effect of the Position of the Axis of Rotation on the Discomfort Caused by Whole-Body Roll and Pitch Vibrations of Seated Persons. J. Sound and Vibration 58:127-141, 1978.

64. GRIFFIN, M. J., K. C. PARSONS and E. M. WHITHAM. Vibration and Comfort IV. Application of Experimental Results. Ergonomics 25:721-739, 1982.

65. SHOENBERGER, R. W. Psychophysical Assessment of Angular Vibration: Comparison of Vertical and Roll Vibrations. Aviat. Space Environ. Med. 50:688-691, 1979.

66. SHOENBERGER, R. W. Psychophysical Comparison of Vertical and Angular Vibrations. Aviat. Space Environ. Med. 51:759-762, 1980.

67. SHOENBERGER, R. W. Discomfort Judgements of Translational and Angular Whole-Body Vibrations. Aviat. Space Environ. Med. 53:454-457, 1982.

68. SJOFLOT, L. and C. W. SUGGS. Human Reactions to Whole-Body Transverse Angular Vibrations Compared to Linear Vertical Vibrations. Ergonomics 16:455-468, 1973.

69. HARRAH, C. B. and R. W. SHOENBERGER. Effect of Body Supination Angle on Subjective Response to Whole-Body Vibration. Aviat. Space Environ. Med. 52:28-32, 1981.

70. GUIGNARD, J. C. Ch. 7: Pathological Effects of Vibration. *Aeromedical Aspects of Vibration and Noise*, J. C. GUIGNARD and P. F. KING (eds.), AGARD, Neuilly-sur-Seine, France, 67-72, 1972.

71. FRYMOWER, J. W., M. H. POPE, M. C. COSTANZA, J. C. ROSEN, J. E. GOGGIN and D. G. WILDER. Epidemiologic Studies of Low-Back Pain. Spine 5:419-423, 1980.

72. WILDER, D. G., B. B. WOODWORTH, J. W. FRYMOWER and M. H. POPE. Vibration and the Human Spine. Spine 7:243-254, 1982.

73. ANDERSSON, G. B. J., R. W. MURPHY, R. ORTENGREN and A. L. NACHEMSON. The Influence of Backrest Inclination and Lumbar Support on Lumbar Lordosis. Spine 4:52-58, 1979.

74. SHANAHAN, D. F. and T. E. READING. Helicopter Pilot Back Pain: A Preliminary Study. Aviat. Space Environ. Med. 55:117-121, 1984.

75. CARLSÖÖ, S. The Effect of Vibration on the Skeleton, Joints and Muscles: A Review of the Literature. Applied Ergonomics 13:251-258, 1982.

76. GRIFFIN, M. J. A Study of Vibration, Pilot Vision and Helicopter Accidents. *AGARD CP-145: Vibration and Combined Stresses in Advanced Systems*, H. E. VON GIERKE (ed.), AGARD, Neuilly-sur-Seine, France, B16-1 to B16-B-1, 1975.

77. GRIFFIN, M. J. and C. H. LEWIS. A Review of the Effects of Vibration on Visual Acuity and Continuous Manual Control, Part I: Visual Acuity. J. Sound and Vibration **56**:383-413, 1978.

78. GRETHER, W. F. Vibration and Human Performance. Human Factors **13**:203-216, 1971.

79. LEWIS, C. H. and M. J. GRIFFIN. A Review of the Effects of Vibration on Visual Acuity and Continuous Manual Control, Part II: Continuous Manual Control. J. Sound and Vibration **56**:415-457, 1978.

80. CATTERSON, A. D., G. N. HOOVER and W. F. ASHE. Human Psychomotor Performance During Prolonged Vertical Vibration. Aerospace Med. **33**:598-602, 1962.

81. CLARKE, N. P., G. C. MOHR, J. W. BRINKLEY, P. J. MARTIN, H. C. WOODING, J. H. HENZEL and H. E. VON GIERKE. Evaluation of Peak vs. RMS Acceleration in Periodic Low Frequency Vibration Exposures. Aerospace Med. **36**:1083-1089, 1965. (also published as AMRL-Tech. Rep.-65-67).

82. HARRIS, C. S., W. D. CHILES and R. M. TOUCHSTONE. Human Performance as a Function of Intensity of Vibration at 5 CPS. AMRL-Tech. Rep.-64-83, Aerospace Medical Research Laboratories, Wright-Patterson, Air Force Base, OH, U. S. A., 1964.

83. HOLLAND, C. L. Performance Effects of Long-Term Random Vertical Vibration. Human Factors **9**:93-104, 1967.

84. HORNICK, R. J. and N. M. LEFRITZ. A Study and Review of Human Response to Prolonged Random Vibration. Human Factors **8**:481-492, 1966.

85. TORLE, G. Tracking Performance Under Random Acceleration: Effects of Control Dynamics. Ergonomics **8**:481-486, 1965.

86. WEBB, R. D. G., M. D. BENNETT, B. FARMILO, S. H. COLE, S. J. PAGE and W. R. WITHEY. Personality and Inter-Subject Differences in Performance and Physiological Cost During Whole-Body Vibration. Ergonomics **24**:245-255, 1981.

87. WILKINSON, R. T. and R. GRAY. Effects of Duration of Vertical Vibration Beyond the Proposed ISO 'Fatigue-Decreased Proficiency' Time, on the Performance of Various Tasks. *AGARD Conference Proceedings No. 145: Vibration and Combined Stresses in Advanced Systems*, H. E. VON GIERKE (ed.), AGARD, Neuilly-sur-Seine, France, B19-1 to B19-5, 1975.

88. LEWIS, C. H. and M. J. GRIFFIN. The Interaction of Control Gain and Vibration with Continuous Manual Control Performance. J. Sound and Vibration **55**:553-562, 1977.

89. LEWIS, C. H. and M. J. GRIFFIN. Mechanisms of the Effects of Vibration Frequency, Level and Duration on Continuous Manual Control Performance. Ergonomics **22**:855-889, 1979.

90. GAUTHIER, G. M., J. P. ROLL, B. MARTIN and F. HARLAY. Effects of Whole-Body Vibrations on Sensory Motor System Performance in Man. Aviat. Space Environ. Med. **52**:473-479, 1981.

91. ROLL, J. P., B. MARTIN, G. M. GAUTHIER and F. MUSSA IVALDI. Effects of Whole-Body Vibration on Spinal Reflexes in Man. Aviat. Space Environ. Med. **51**:1227-1233, 1980.

92. MARTIN, B., G. M. GAUTHIER, J. P. ROLL, M. HUGON and F. HARLAY. Effects of Whole-Body Vibrations on Standing Posture in Man. Aviat. Space Environ. Med. **51**:778-787, 1980.

93. HARRIS, C. S. and R. W. SHOENBERGER. Combined Effects of Broadband Noise and Complex Waveform Vibration on Cognitive Performance. Aviat. Space Environ. Med. **51**:1-5, 1980.

94. SCHMITZ, M. A., A. K. SIMONS and C. A. BOETTCHER. The Effect of Low-Frequency, High-Amplitude Whole Body Vertical Vibration on Human Performance. Report No. 130, Bostrom Research Laboratories, Milwaukee, Wisconsin, 1960.

95. SHOENBERGER, R. W. Effects of Vibration on Complex Psychomotor Performance. Aerospace Med. 38:1264-1269, 1967.

96. SHOENBERGER, R. W. Mechanisms of Vibration Effects on Aircrew Performance. *AGARD CP-145: Vibration and Combined Stresses in Advanced Systems*, H. E. VON GIERKE (ed.), AGARD, Neuilly-sur-Seine, France, B17-1 to B17-9, 1975.

97. INTERNATIONAL ORGANIZATION FOR STANDARDISATION. Guide for the evaluation of human exposure to whole body vibration. ISO-2631, 1978. (Amended 1982).

98. TEMPLE, W. E., N. P. CLARKE, J. W. BRINKLEY and M. J. MANDEL. Man's Short Term Tolerance to Sinusoidal Vibration. Aerospace Med. 35:923-930, 1964.

99. OBORNE, D. J. Whole-Body Vibration and International Standard ISO 2631: A Critique. Human Factors 25:55-70, 1983.

100. Vibration Exposure Limits. Advisory Publication 61/1, Air Standardization Coordinating Committee, 1977.

101. BALMFORD, D. E. H. Control of Vibration in Helicopters. Aeronaut. J. 81:63-67, 1977.

102. JOHNSON, J. C. and D. R. PRISER. Vibration Levels in Army Helicopters -- Measurement Recommendations and Data. Report No. 81-5, U. S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama 36362, 1981.

103. STEELE-PERKINS, A. P. Helicopter Crew Comfort. Unpublished paper, Institute of Aviation Medicine, Farnborough, England, 1981.

104. HARPER, H. P. Advances in Helicopter Cockpit Technology. *AGARD CP-255: Operational Helicopter Aviation Medicine*, S. C. KNAPP (ed.), AGARD, Neuilly-sur-Seine, France, 24-1 to 24-7, 1978.

105. MORDOFF, K. F. Sikorsky Pursues Sidearm Controls in Cockpit Design. Aviation Week & Space Technology, 74 - 79 (May Issue), 1983.

106. SINCLAIR, M. Flight Experiments With Integrated Isometric Side-Arm Controllers in a Variable-Stability Helicopter. *AGARD Conference Proceedings No. 333: Criteria for Handling Qualities of Military Aircraft*, AGARD, Neuilly-sur-Seine, France, 14-1 to 14-9, 1982.

107. LAMBERT, A. M. Flying the Hughes AH-64 Apache. Interavia (English) 38:833-836, 1983.

108. CRESSMAN, P. W. Anthropometric Survey Of COH58A 'Kiowa' Helicopter. Technical Memorandum No. 879, DCIEM, Downsview, Ontario, Canada, 1972.

109. HEARON, B. P. and J. H. RADDIN, JR. Experience with Highly Selective Screening Techniques for Acceleration Stress Duty. *AGARD Conference Proceedings CP-310: the Effects of Long-Term Therapeutics, Prophylaxis and Screening Techniques on Aircrew Medical Standards*, AGARD, Neuilly-sur-Seine, France, A5-1 to A5-7, 1980. (37th meeting of the Aerospace Medical Panel, Downsview, Ontario).

110. THOMAS, D. J., P. L. MAJEWSKI, C. L. EWING and N. S. GILBERT. Medical qualification procedures for hazardous-duty aeromedical research. *AGARD Conference Proceedings No. 231: Prospective Medicine Opportunities in Aerospace Medicine*, J. TRIEBWASSER (ed.), AGARD, Neuilly-sur-Seine, France, A3-1 to A3-13, 1977.

111. KAZARIAN, L. E. and W. F. BELK. Flight Physical Standards of the 1980's: Spinal Column Considerations. AMRL-Tech. Rep.-79-74, Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, U. S. A., 1979.

112. WHITE, A. H. *Back School and Other Conservative Approaches to Low Back Pain*. The C. V. Mosby Company, St. Louis, 1983.

113. ZACHRISSON FORSSELL, M. The Back School. Spine 6:104-106, 1981.

114. DESJARDINS, S. P., D. H. LAANANEN and G. T. SINGLEY, III. Aircraft Crash Survival Design Guide. USARTL-Tech. Rep.-79-22, Applied Technology Laboratory, U. S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia 23604, 1980. (in 5 volumes).

115. POIRIER, J. L. Transmissibilité des vibrations a travers différents coussins de siége d'hélicoptère. Medecine Aeronautique et Spatiale, Medicine Subaquatique et Hyperbare 18:262-269, 1979.

116. COBLENTZ, A., Y. DELOISON, G. IGNAZI and J. PRUDENT. Utilisation d'une Method de Biostéreometrie Dans la Conception d'un Poste de Pilotage d'Hélicoptère. *AGARD CP-255: Operational Helicopter Aviation Medicine*, S. C. KNAPP (ed.), AGARD, Neuilly-sur-Seine, 29-1 to 29-19, 1978. (in French).

117. KELSEY, J. L. Idiopathic Low Back Pain: Magnitude of the Problem. *American Academy of Orthopaedic Surgeons Symposium on Idiopathic Low Back Pain*, A. A. WHITE and S. L. GORDON (eds.), The C. V. Mosby Company, St. Louis, U. S. A., 5-8, 1982.

118. ORTENGREN, R., G. B. J. ANDERSSON and A. L. NACHEMSON. Studies of Relationships Between Lumbar Disc Pressure, Myoelectric Back Muscle Activity, and Intra-Abdominal (Intragastric) Pressure. Spine 6:98-103, 1981.

119. *Dorland's Illustrated Medical Dictionary, Twenty-Fifth Edition.* W. B. Saunders, Philadelphia, 1974.

Appendix A:

Glossary of terms used in this report

Annulus Fibrosus:
(annulus fibrosus disci intervertebralis) the outer ringlike part of the intervertebral disc, composed of fibro-cartilage and fibrous tissue.

Coronal Plane:
The three mutually-perpendicular geometric planes used in describing projections or angles within the body are the coronal (or frontal) plane, the transverse plane and the sagittal plane. The coronal plane is the vertical plane that is parallel to the coronal suture of the skull, and by extension, is parallel to the line between the shoulders, hips, etc. The sagittal plane is the vertical plane perpendicular to this. (Recall Sagittarius, the archer, and the vertical plane in which he holds his bow.) The transverse plane is horizontal.

Dorsal: pertaining to a position or surface which is towards the back.

Epiphysial:
pertaining to the *Epiphyses*, the ends of long bones, or the faces of the vertebrae which are attached to the intervertebral discs.

Fibrocartilaginous:
made up of fibrocartilage, a type of cartilage in which normal cartilage cells are surrounded by parallel, thick, compact collagenous bundles forming the interstitial substance.

Flexion: the act of bending; in the spine, this means bending forward.

Foramina:
plural of *Foramen*, a natural opening or passage.

Herniated:
protruding like a hernia. A *herniated intervertebral disc* has a rupture of the *annulus fibrosus* which allows the *nucleus pulposus* to protrude, usually into the spinal canal.

Hypocapnia:
"a deficiency of carbon dioxide in the blood, resulting from hyperventilation and eventually leading to alkalosis."[119]

Idiopathic:
a word used to describe a disease of spontaneous origin, i. e., which arises from no other known disease or injury. Alan C. Burton (personal communication) said that doctors applied this description to any disease they could not explain. "Idiopathic low-back pain" is that back pain which is not associated with known injuries, congenital malformations, or diseases such as cancer.

Ilium: "the expansive superior part of the hip bone."[119]

Interspinalis:
pertaining to the short bands of muscle fibres between spinous processes of contiguous vertebrae.

Intertransversearii:
(musculi intertransversarii laterales lumborum) muscles passing between the transverse processes of adjacent lumbar vertebrae.

Kinesthetic:
pertaining to the sense by which the positions of joints and muscles are known.

Kyphosis: "abnormally increased convexity in the curvature of the thoracic spine as viewed from the side."[119] In this essay, as in many discussions of the spine, *lordosis* and *kyphosis* refer to a curvature of the spine which is either convex to the front or to the back, respectively.

Lordosis: See *kyphosis* above.

Lumbo-sacral:
pertaining to the connection between the lumbar spine and the sacrum.

Multifidus:
one of a number of muscles originating in the sacrum, sacroiliac ligament, mammilary processes of the lumbar vertebrae, transverse processes of the thoracic vertebrae and articular processes of the cervical vertebrae which insert on the spines of the vertebrae immediately above and act to rotate or extend the spine.

Myoelectric:
pertaining to electro-myography, the measurement of electrical signals from muscles.

Nucleus Pulposus:
(nucleus pulposis disci intervertebralis) a semi-fluid mass (gel-like) which forms the central part of the intervertebral disc.

Osteoarthritis:
"degenerative joint disease....characterized by degeneration of the articular cartilage, hypertrophy of the bone at the margins, and changes in the synovial membrane."[119]

Osteochondrosis:
"a disease of the growth or ossification centres in children which begins as a degeneration or necrosis followed by regeneration or recalcification."[119]

Paravertebral:
"beside the vertebral column."[119]

Paresthesias:
abnormal sensations, such as "pins and needles" which may arise from damaged nerves, among other causes.

Psoas: The *Psoas major* and *Psoas minor* muscles originate in the lumbar vertebrae and fascia and insert on the lesser trochanter of the femur (major) or the lower part of the ilium. They act to flex the trunk. The *psoas major* also flexes and rotates the thigh.

Quadratus:
(musculus quadratus lumborum) one of two muscles which originates in the iliac crest, the thoracolumbar fascia and the lumbar vertebrae and inserts on the twelfth rib and the transverse processes of the four upper lumbar vertebrae. They act to flex the lumbar vertebrae laterally.

Rectus abdominis:
a vertical band of muscle between the pubis and the lower ribs. It acts to flex the spine forwards and to contain the abdomen.

Sacrospinalis:
also *(musculi erector spinae)* a name given to the more superficial of the deep muscles of the back, which originate in the sacrum and in the spines of the lumbar and lower thoracic vertebrae and insert upwards in the spine and head.

Scoliosis: a lateral deviation of the spine, as viewed from the rear.

Spondylolisthesis:
"forward displacement of one vertebra over another..."[119]

Spondylolysis:
"dissolution of a vertebra..."[119] This term is used to describe a separation of the vertebral arch and processes from the vertebral body, which allows the latter to slip relative to the lower vertebral body. The condition referred to in this report is

particular to the lowest lumbar vertebra.

Transversalis:

(musculi transversus abdominis) a muscle which encloses the sides of the abdomen, originating at the spine and lower ribs, and inserting at the sides of the *rectus abdominis* and the pubis.

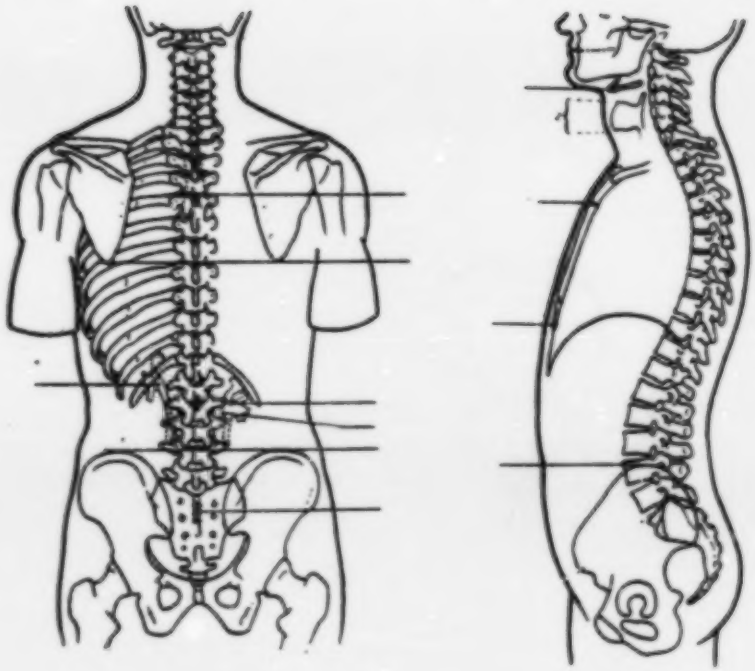

Figure 1. The Vertebral Column, reproduced from Kleitz and Delahaye.[22]

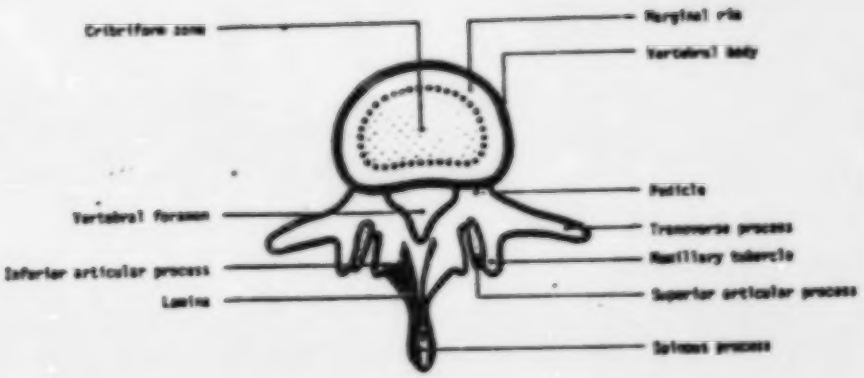

Figure 2. Morphology of a thoracic or lumbar vertebra, reproduced from Kleitz and Delahaye.[22]

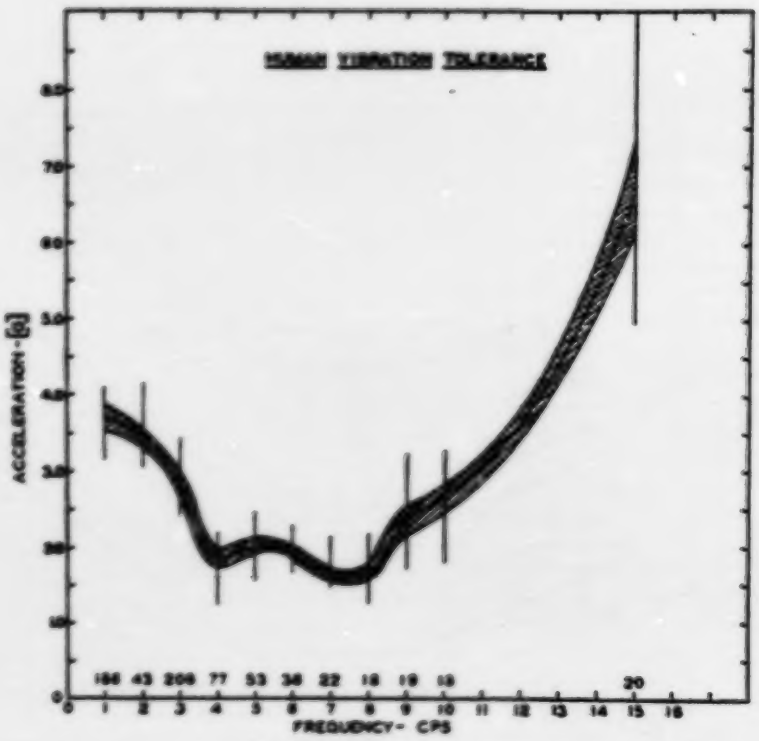

Figure 3. Limits of human voluntary tolerance to vertical sinusoidal vibration in the seated position, as found by Magid *et al.*[54]

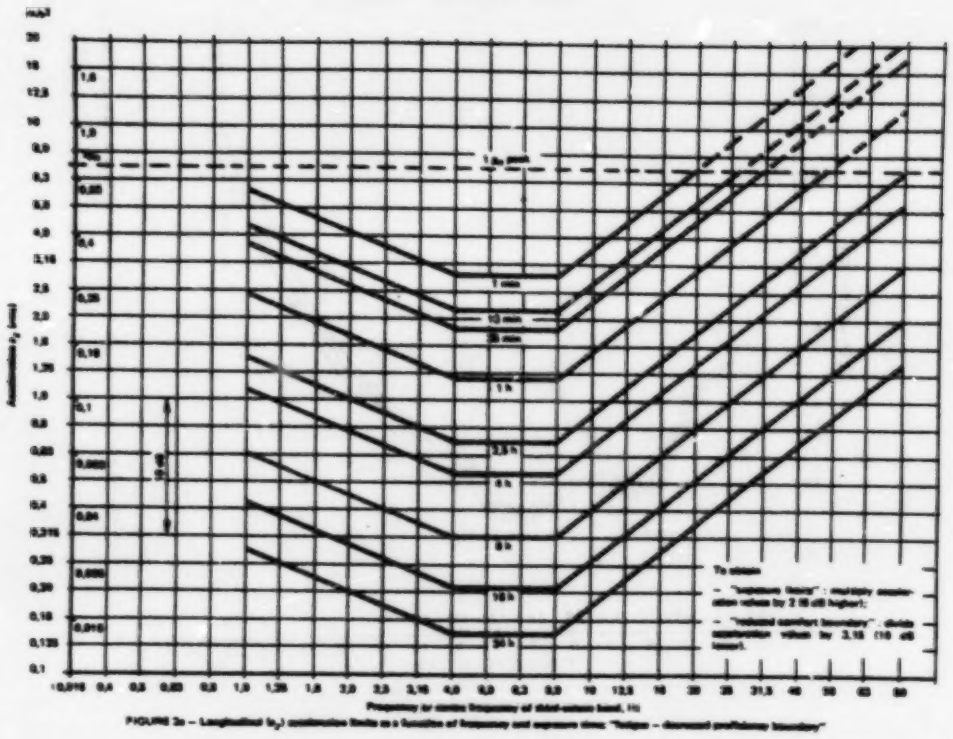

Figure 4. Longitudinal (vertical) r. m. s. acceleration limits as a function of frequency and exposure time from ISO 2631-1978.[97] These graphs are for the "Fatigue-Decreased Proficiency" levels. Other limits are determined as indicated at the lower right.

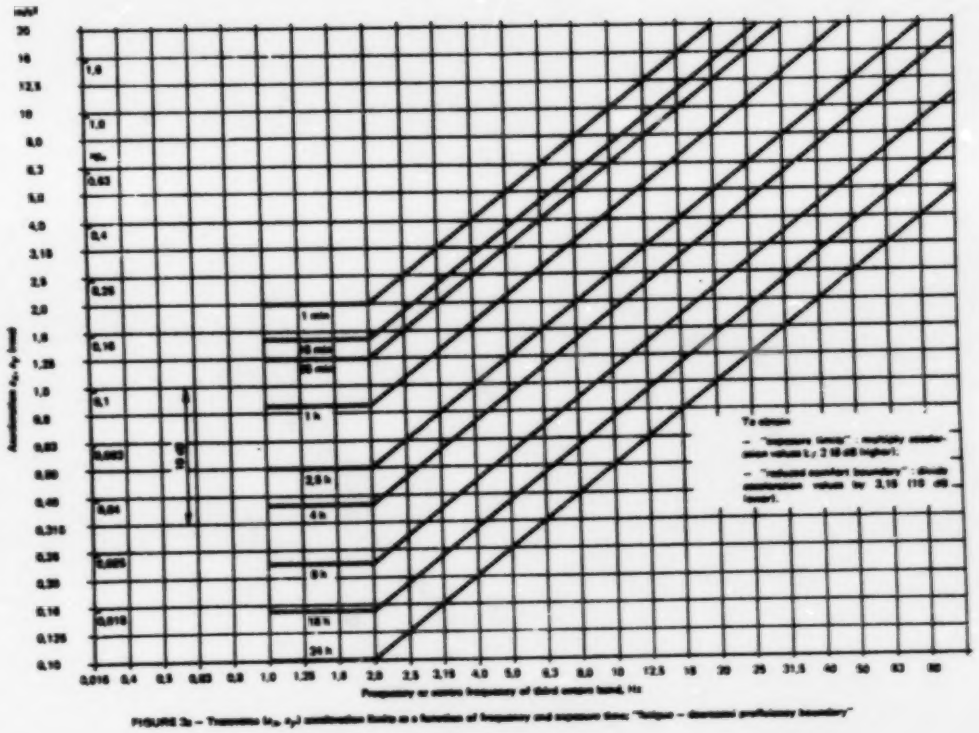

Figure 3. Transverse (horizontal) r. m. s. acceleration limits as a function of frequency and exposure time from ISO 2631-1978.[97] These graphs are for the "Fatigue-Decreased Proficiency" levels. Other limits are determined as indicated at the lower right.

POOR

QUALITY

ORIGINAL